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WIND-SHEAR ENCOUNTERS DURING VISUAL APPROACHES AT NIGHT. A PILOTED SIMULATOR STUDY.

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SUMMARY

A study has been made in a fixed-base simulator of encounters with a variety of idealised wind-shears under conditions simulating a two-pilot approach, partly on instruments and partly visual, made at night.

Twenty-five pilots, airline and Service, participated completing a total of 62 sorties, each of ten approaches. There were four shear encounters per sortie. The data comprised time-histories of each approach together with the pilots' responses to a detailed questionnaire and their spontaneous observations.

Pilots were successful in recognising the absence of shear or the presence of severe shear. They were less successful in recognising shears of moderate intensity or in identifying the velocity components. They were prone to discern vertical draughts where none existed and may have been induced to do so by the compelling visual indications of vertical departure from the glide path given by the Precision Approach Path Indicator (PAPI).

To cope effectively with the shears, pilot action had to be both prompt and appropriate and it was clear that pilots were quick to seek clues that might offer 'early warning' of impending shear. Many pilots commented on the value of participating in this study and it seems likely that the inclusion of shear encounters during routine simulator training may prove beneficial.

Departmental Reference: FS 112

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1 INTRODUCTION

The work which is the subject of this Report formed part of the UK Wind Shear Study Programme and was concerned with simulated encounters with a variety of wind shears on the approach, in good visibility, at night, using one of four approach techniques.

The objectives were to assess pilots' ability to recognise the presence of low-level wind shear and to analyse the components present; to establish the cues on which these judgements were based; to observe the control inputs made in response to the shear and to assess their efficacy in countering its effects; and to assess the influence of the shear on overall landing performance.

The intention had been to use staff of the Aeronautical Instrumentation Laboratory of the Cranfield Institute of Technology (CIT) under extra-mural contract to develop the simulation, to run the programme on the No.2 simulator at RAE Bedford and to analyse the results. Unexpected problems of manning led, in the event, to the simulation being designed by RAE, developed by RAE with assistance from CIT, run by CIT under general RAE direction and analysed by RAE.

2 DESCRIPTION OF THE EXPERIMENT

2.1 The simulator

The No.2 simulator of Flight Systems Department, RAE Bedford has been described in detail elsewhere[1] and only a brief resumé of its salient features will be given here. The simulator is essentially fixed-base though vibration can be applied to the cockpit to give some representation of the effects of turbulence. The cockpit was configured to represent a twin-engined turbo-jet aircraft (Fig 1) and the flight characteristics were broadly typical of 'medium' twin-jets, though they did not represent any specific aircraft: the operating mass of the simulated aircraft was around 47000 kg and the maximum thrust available was 120 kN.

The visual display was digitally generated and consisted of a standard runway and approach lighting pattern together with Precision Approach Path Indicators (PAPI), as seen at night; the whole being positioned and orientated to comply with the aircraft's position and attitude. Fig 2 shows the lighting pattern as seen from a height of 215 ft, 4300 ft from the glide path origin; note that the threshold lights (green) and the inner PAPIs (red) appear smaller than they actually are, due to differential sensitivity of the film. At the

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time of these experiments the visual display was available to the pilot-in-command (P1) only; P2 had no visual presentation and remained on instruments throughout.

2.2 Types of approach

Each approach began with the aircraft at a point on the extended centre-line of 'Runway 36' about 6.5 n mile from the threshold and at a height of about 1900 ft. At the start, the aircraft was in straight, steady, trimmed level flight in the landing configuration (gear down; flaps 60°) with the thrust set to give the 'normal' approach airspeed of 125 kn. Heading was set to maintain a track of 360° with the current wind model.

All runs represented approaches at night with complete cloud cover down to 500 ft, and cloudless conditions with excellent visibility below 500 ft. The runway had an ILS with 3° glide slope and the glide-path origin was 305 m (1000 ft) beyond the runway threshold. A non-directional beacon (NDB) was co-located with the outer marker.

The simulator could be programmed to represent the variations in space of the three orthogonal components of air velocity. A repertoire of such 'shears' was developed that seemed representative of real events in the atmosphere, and these formed the primary variable in the experiments. They are described in detail in a later section.

The task was essentially a two-pilot, shared approach using one of four procedures, namely:

A1 Automatic landing. Decision height 50 ft. Auto-pilot and auto-throttle to be disengaged on touchdown*.

A2 Coupled ILS approach (auto-pilot and auto-throttle) with manual landing. Decision height 200 ft, at which auto-pilot and auto-throttle were to be disengaged.

A3 Manual ILS (directed) with manual landing. Decision height 300 ft.

A4 Non-precision, using automatic direction-finder (ADF). Decision height 400 ft.

The programme was so arranged that there were roughly twice as many coupled or manual ILS approaches as there were autolands or non-precision approaches.

* There was no 'kick-off-drift' facility in auto-land. If disengagement on touchdown led to loss of directional control during the ground roll this was not regarded as a failure.

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The three components of air velocity together with selected control and response variables were recorded throughout each approach on two eight-channel pen recorders. Pilots' comments and decisions (eg regarding choice of approach speed) were recorded at the time by the supervisor of the simulation, as were their responses to a detailed questionnaire which they were taken through after each run.

2.3 Organisation

Two test pilots from CIT participated in the development of the simulation and, in particular, in the selection of the shears to be employed in the main experiment from the much wider range of candidate shears put forward initially. The object here was to choose shears that were within the performance capability of the aircraft but which were 'unforgiving' of substantial departures from optimum response by the pilot. The pilots employed in this phase were excluded from the main experiment on the grounds that their familiarity with the shears might introduce a bias.

Twenty-five practising pilots participated in the main study: twelve of these were Service pilots based at RAE Bedford, of whom six were graduates of ETPS, the national test pilots' school, with background experience mainly in fighter/strike aircraft; experience in the non-test-pilot group of Service pilots was either mainly on 'heavy' aircraft, or covered a wide spectrum: twelve pilots were co-opted from British Airways, one being a former test-pilot: there was one civilian test pilot having extensive experience of large transport aircraft. Experience in terms of flying time ranged from about 1700 h to over 10000 h. Prior to participation, all pilots had been asked to read (a) a document outlining the aims of the trial and (b) the CAA Information Circular on Wind Shear[2].

In the 'standard' pattern, on first arriving at the simulator, each pair of pilots was given a general briefing on the exercise and was shown the simulator's flight-deck layout, etc. Following a more detailed briefing on procedures (described in the next section) the pilots undertook a practice session to familiarise themselves with the simulator, to clarify their roles as P1 and P2 in the context of the four approach techniques and to agree on cockpit drills, overshoot procedures, etc. When the pilots declared themselves sufficiently familiarised the first experimental sortie of ten approaches could be started; at this point the crew knew only that some runs would contain shear while the rest would not and that this mixture would be combined randomly with the four

types of approach. The supervisor announced the type of approach for the first run and also gave information setting the scene; an operator at the external control desk set up the pre-arranged wind pattern and started the recorders. The run commenced with the initial conditions described earlier. During each run the supervisor recorded the crews' decisions and comments and, after the run had ended, he recorded answers to the questionnaire and any other comments while the control-desk operator set up the wind pattern for the next run; this cycle was repeated until the sortie of ten approaches had been completed, which usually took rather less than 1 h. The pilots then exchanged roles for the second sortie which, of course, presented a different combination of shears and approach types. In most cases preparation, briefings, familiarisation, completing two sorties (one as P1, the other as P2) and de-briefing after each, occupied the better part of a normal working day when dealing with two visiting pilots, though occasionally three or, more rarely, four sorties were achieved in a day.

Several of the Service pilots were familiar with the simulator when the trial started or became so as it progressed and for these the later briefings were suitably abbreviated, as were the periods devoted to re-familiarisation, though some re-familiarisation was given whenever the interval between sorties was a day or more.

Because the availability of the Service pilots fluctuated in response to other demands made on their time, no attempt was made to adhere rigidly to the 'standard' two-sortie pattern described above though it was achieved in the majority of cases.

2.4 Pilot briefing

The salient features of the briefing are given below:

(1) In a sortie of ten approaches there would be a mixture of wind shear and normal conditions, combined randomly with the four types of approach. All approaches would be 'straight in' from the initial conditions specified in section 2.2.

(2) Immediately before the start of each approach the supervisor would announce the type of approach to be made and would also give an 'ATC-style' statement on the current weather conditions, runway state and any other relevant information (such as reports of shear encounters by preceding aircraft)*. In

* For example "The next run will be a manual ILS. The surface wind is 150/05, gusting 15. The weather is squally and thunderstorms are active in the area. The runway is wet."

announcing the approach procedure the supervisor would remind pilots of the appropriate decision heights, which were:

A1	50 ft	
A2	200 ft	- at which point auto-pilot and auto throttles were to be disengaged
A3	300 ft	
A4	400 ft	

For ADF approaches (A4) the supervisor would supply a tabulation of target heights for 15 s intervals from the outer marker for a suitable range of groundspeeds. Groundspeed and drift were to be estimated by the crew from the given surface wind.

(3) Shared approach procedures were to be used. P2 would accept the aircraft at the start of each run and would fly it (on instruments) until P1 took over for the final stages of the approach and the landing. Handover was to be on P1's call which could be when he had the runway in sight (500 ft) or at Decision Height or at any point in between.

(4) Each pair of pilots was briefed to decide between themselves what calls and responses they would use - this enabled them to use the forms with which they were most familiar.

(5) The runway heading was 360° and this was to be taken as the only runway in use*.

(6) For each approach, a successful outcome would be either a safe landing or the initiation of a safe overshoot. In the latter case the simulation run would end once a positive rate of climb had been established at an airspeed above that for stall-warning (just below 100 kn).

(7) Pilots were requested to comment as they wished during and after the approach, told that they would be taken through the questionnaire (shown in the Appendix) after each run and were familiarised with its contents and purpose.

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* While accepting this for the purposes of this experiment, a number of pilots pointed out that in appropriate circumstances in real life they would normally have requested use of another runway or, if this was not available, would have diverted or held.

2.5 Wind shears

Five classes of air velocity distribution were specified:

Basic (ie flat profiles (FP) and normal boundary layers (NBL))
Unusual boundary layers
Low-level jets
Fronts
Storms.

The descriptive framework comprised a vertical reference plane through the extended centre-line of the runway in which the orthogonal components of velocity, u , v and, in the case of storms only, w were specified as functions of x and H as described below. This formulation was necessitated by the inherent limitations of the computer and implied, unfortunately, that phenomena that were truly three-dimensional, such as the storms, were perforce represented by a two-dimensional cross-section, so that deviations of the flight path from the reference plane were not accompanied by changes in air velocity. The exact significance of this distortion is not known, but it is believed to be fairly small even for the storms.

'Turbulence' was simulated by superimposing components derived from filtered white noise onto the mean wind profiles. The rms turbulence velocities were 2 ft/s.

2.5.1 Basic profiles

(a) Flat profiles

In these the wind velocity was invariant with height. Fourteen wind conditions were specified - Calm; 360/05; 360/30; 330/30; 300/05; 300/15; 270/15; 240/10; 180/05; 120/10; 090/05; 030/05; 030/10; 030/30.

(b) Normal boundary layers

These used the velocities specified above as surface winds (V_0) but introduced additional variations with height, thus;

(a) the wind speed at 1000 ft was three times the value at the surface and the wind did not change further above 1000 ft,

(b) the variation of wind speed with height up to 1000 ft was linear above and below 350 ft and the speed at 350 ft (V_{350}) was

$$V_{350} = 7V_0/3 .$$

An exception to this rule was made for surface winds of 30 kn where V_{1000} was taken as 60 kn and V_{350} as 50 kn.

2.5.2 Abnormal boundary layers

Five profiles were specified that differed from the normal boundary layer in that the 'corner' height was set at 50 ft or 150 ft rather than 350 ft, though V_{350} (as defined above) was used as the windspeed at the 'corner', with linear interpolation between the surface wind, the 'corner' and the 1000 ft wind.

The preliminary assessment referred to in section 2.2 indicated that these profiles were, in the main, not particularly hazardous and only one was retained for the main study. The profile for this case (W1) is illustrated in Fig 3: here, and elsewhere the rounding of the 'corners' from the linearised form was a consequence of the analogue methods used to implement the model.

Profiles of generally similar form to these abnormal boundary layers have been deduced from detailed analysis of flight records, in particular, from Concorde airline operations.

2.5.3 Low-level jets

Five profiles were specified in which symmetrical low-level jets peaking at 300 ft were superimposed on flat profiles. In the event, two of these were employed in the main study and these profiles (W2, W3) are illustrated in Fig 4.

Low level jets usually occur at night when a strong inversion has developed. In practice they tend to occur at rather greater heights than that employed here, which was chosen with the aim of intensifying the difficulties at a late stage in the approach.

2.5.4 Fronts

The feature being imitated here was the large change in wind direction that can occur as a front is traversed. Two of the four profiles considered were chosen for the main study and these (W4, W5) are illustrated in Fig 5; note that the changes of direction occurred over distances in the region of half a mile and were centred about 1 mile from the threshold. The variation of wind with height conformed with the 'normal boundary layer' defined in section 2.5.1(b).

2.5.5 Storms

Storm cells were assumed to be symmetrical about a vertical axis, the position of which was assumed to be fixed throughout a given approach; the horizontal winds were assumed to flow radially outwards from the axis and were specified as functions of distance from it as well as of height. As noted earlier, because of

computer limitations, the winds encountered by the aircraft could not be varied as functions of lateral displacement from the vertical plane containing the glide-path and were in fact fixed at the values occurring in that plane.

All storm cells contained vertical draughts and it was assumed that, at heights above 100 ft, these were of constant magnitude within a circular cylindrical core centred on the axis and decreased linearly to zero with increasing radius over an annulus surrounding the core. Below 100 ft the intensity of the draughts decreased linearly with height, falling to zero at ground level. In this case also the draughts encountered by the aircraft were perforce limited to the values that existed in the vertical plane containing the glide-path, ie, they could not be varied with lateral displacement from that plane.

Apart from the deficiencies noted, the models employed here were broadly consistent with the generally accepted structure of storm cells.

The position and intensities of the storm cells could be varied to provide a wide range of combined horizontal and vertical velocity fields, and much of the preliminary assessment was devoted to the selection of a small repertoire for use in the main study.

The elements of the profiles eventually selected (W6, W7, W8) are illustrated in Figs 6, 7, 8 and 9: Fig 6 shows the basic variation of windspeed with height; Fig 7 shows the variation, with horizontal distance, of the multiplying factor, K, applied to the basic profile; Fig 8 shows the variation of wind direction with horizontal distance from the axis - note that since the storms cells for W6 and W8 were centred on the extended centre-line, the wind changed abruptly as the axis of the storm was crossed, whereas the storm cell for W7 was offset 2000 ft laterally and so produced a more progressive change of wind on the centre-line; Fig 9 shows the variation in downdraught intensity with distance from the storm centre - peak intensity was the same (20 ft/s) for all storms, note however the shorter duration of the downdraught encountered in W7 which was a result of the lateral offset of this storm cell. To give a clearer picture of the results of combining the various elements described, Fig 10 shows the variation with height and range (from the glide-path origin) of the velocity components that would be encountered on a 1:20 glideslope through each of the storm cells. All the cells considered here had their axes centred at a distance of 4500 ft from the threshold (5500 ft from GP origin) measured along the extended centre-line.

It will be appreciated that the detailed structures of particular severe storms are still the subject of some debate, based as they are on the interpretation of less-than-complete information obtained from records of accidents or near-accidents. Data derived from one such analysis[3] have been included in Fig 10 for comparison - they relate to an L-1011 (Aircraft I) that overshot from JFK airport on 24 June 1975 shortly before the B-727 (Aircraft L) crashed there following a shear/downburst encounter. The data refer, of course, to the actual flightpath which, in its later stages, was well below the standard 3° glide-path, thus they are not directly comparable to the model illustrated: however, the strong family resemblance suggests that the models used in this simulation offer a reasonable approximation to intense shears encountered in real life.

Due to errors in programming, the storm W8 was presented initially with more intense horizontal shears than had been intended, and unfortunately the error was not detected until several sorties involving it had been completed. These encounters have, in the main, been excluded from the analysis, though some useful information was obtained from their earlier stages: the shear is referred to as W8A.

3 RESULTS AND DISCUSSION

The 25 pilots who took part in the main study completed a total of 62 sorties, each of ten runs: five additional runs from a partly-completed sortie have been included in the analysis, giving a total of 625 runs of which 250 contained some form of intentional wind shear.

The size of this data base, combined with the nature of some of the questions we have sought to answer with its aid, made inevitable the use of some statistical methods of analysis - even though we have slight reservations as to the propriety of applying such methods to relationships that involve the skill and judgement of a highly specialised population (in this case, the participating pilots). We have made considerable use of statistical methods to test the significance of apparent associations, for example, between the occurrence of a phenomenon and the presence or absence of a particular factor. For those who, like the authors, have only a distant acquaintance with statistics it should be said that the methods involve formulating the so-called 'Null Hypothesis' (ie, that the apparent association is not 'real') and then assessing the probability of the observed result having arisen by chance (for example by applying methods such as the χ^2-test or 'Student's' T-test, as appropriate): clearly the lower this

probability is, the more likely is the association to have been a valid one. In verbal description we have used a convention that seems widely accepted among statisticians, though again with some reservations:

Description	Probability (p) of an apparent association occurring by chance
Not significant	$p > 0.05$
Probably significant	$0.05 \geq p > 0.01$
Significant	$0.01 \geq p > 0.001$
Highly significant	$p \leq 0.001$.

In this context it is important to remember that statements that a particular association is 'not significant' mean only that it is not proven in conventional statistical terms. There may still be a conclusion of practical significance to be drawn.

Of the 25 pilots who took part in this study one rated the simulation 'excellent/good', ten rated it as 'good', nine as 'fair', one as 'acceptable' one rated it 'poor' and three made no comment. The major and most common complaints were:

(a) that the visual system, by presenting the lights of a single runway only, eliminated the cues that would normally be available from other lighting patterns in the area (roads, taxiways, other runways, etc) and so created difficulties, especially laterally,

(b) there was a persistent, slight, but seemingly ineradicable nose-up trim change when the auto-pilot was disengaged, which gave rise to some difficulties.

(c) the 'turbulence' seemed unreal, mainly in that it did not change in intensity with wind strength or shear.

Despite these and other criticisms a large majority of the pilots felt that they had benefitted by participating in the study and would be better able to cope should they encounter shears in real life.

3.1 Recognition

Since the term 'wind shear' has come to be used loosely, particularly by pilots, to mean abnormal (or severe) shear, recognition of wind shear will depend in some degree on arbitrary and personal definitions and will be influenced by the susceptibility of the subject aircraft to disturbance by shear, by the approach aids available, and so forth.

Pilots' assessments of the intensities of the shears, ranked on a nine-point scale from 'None' to 'Very Severe' are summarised in Table 1. When six accidental shears were eliminated from the 'non-shear' group* it became evident that 85% of the 'flat profiles' (FP) and 79.5% of the 'normal boundary layers' (NBL) were correctly identified as 'non-shears', while a further 13.5% of FP and 18% of the NBL were rated as no worse than 'moderate' shears.

Of the eight non-shear runs rated as worse than 'moderate', six involved either 30 kn total winds, 15 kn cross-wind components, or both (ie, wind velocity 360/30, 270/15, 330/30 or 030/30). Moreover, about one-third of all 'non-shears' that involved winds of 30 kn were rated as shears; this frequency of occurrence was about twice that for the rest of the non-shear conditions and was statistically a 'probably significant' difference; however, since it applied equally to flat profiles and normal boundary layers the practical significance of this difference - for example as potentially defining a threshold level of 'shear' - is not clear. In passing we may observe that, human fallibility apart, it is not obvious why flat profiles come to be rated as shears at all, except, perhaps, that by omitting the usual variation of wind-speed with height they appeared abnormal to pilots anticipating a conventional gradient. Overall, the frequency of occurrence of shear ratings was slightly higher for the NBL (0.2) than the FP (0.15), though the difference was not significant.

Approaches through flat profiles showed no significant association between the frequency of occurrence of shear ratings and the approach technique employed. By contrast, approaches through normal boundary layers showed a significantly higher frequency of shear ratings when the manual ILS/manual landing technique (A3) was used, but no significant differences between the remaining techniques.

The 'weather reports' made at the start of each run could be divided into those that appeared consistent with a possible shear encounter on the one hand and those that appeared neutral or inconsistent with wind shear on the other. The proportion of non-shear runs rated as shears was virtually the same for both divisions (22/113 for 'pro-shear' reports: 49/255 for 'anti-shear'), suggesting that the weather report did not influence the assessment significantly.

Turning now to the runs that involved intentional shear, the proportion of shear ratings for each class of shear has been plotted in Fig 11 against the 'severity' (defined here as the proportion of runs rated worse than 'moderate').

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* The group that excludes all the intentional shears, W1-W8A

It will be clear from this that recognition rate improved with severity: 100% recognition rate was achieved only for the storms - all of which contained down-draughts in addition to horizontal shears, though most of the latter were less intense than some of the 'non-storm' shears.

The lowest recognition rate in the presence of intentional shear arose with the abnormal boundary layer (W1). The major effects of this shear occurred too late for most pilots to counter properly and often provoked no discernible pilot reaction. Apart from W1, a 'non-shear' rating by the pilot was only rarely accompanied by an absence of corrective action; ie, the encounters were recognised and acted upon, but did not fall within the personal definition being applied at that time by that pilot.

Of 41 runs that contained intentional shears but were rated as non-shear, seven involved automatic landings. Eight involved non-precision approaches (A4) that had been mismanaged to a degree where the pilot (P1) had to recover from a large offset along or across track and the resulting activity may have obscured the shear encounter. In three cases that involved the traverse of fronts, pilots commented on marked wind changes with height but, for some obscure semantic reason, did not classify them as shears.

The non-storm shears, excluding W1, form a group having a fairly homogeneous recognition rate, regardless of shear type. The recognition rate for those runs given a 'pro-shear' weather report (40 shears recognised out of 46) though higher than for those given an 'anti-shear' report (54 shears recognised out of 76) was not significantly different statistically.

By and large the pilots showed a high level of consistency in recognising non-shears and severe shears and, as might be expected, were least successful and consistent in recognising shears that were 'weak' or that occurred too late to be countered effectively.

3.2 Identification of components

The results are summarised in Table 2, which shows under each shear type the number of runs thought by pilots to contain particular velocity components or combinations of components. Differences between Tables 1 and 2 will be observed under some headings; these arose, for example, from the few cases where a formal rating of the shear was not recorded, though the pilot identified the shear components (or vice versa).

A notable feature was the tendency for pilots to discern downdraughts where none existed - a tendency which increased with the severity of the encounter (as defined above). 'Severity' was plotted against the proportion thought by the pilots to contain downdraughts, for each of the classes of shear (Fig 12). The variation was found to be approximately linear and, if data from the 'storms' were included they followed the same relationship. There would appear to be a firm association in the pilots' minds between downdraughts and 'severity' - in this context it is interesting to note that although storms W8A differed from W8 'only' in having more intense horizontal shears, the downdraughts being the same in both cases, this difference seems to have been interpreted as an increase in the severity of the downdraught, to judge by pilots' comments, and all encounters with W8A were rated 'very severe'. Of 140 runs that were assessed as containing vertical draughts (W_g) only 75 in fact did so. In all, 92 runs contained vertical draughts.

The low-level jet W3 was the only shear in the programme to contain a single component (U_g) and this was comparable in intensity with the horizontal shears encountered at Kennedy (according to Fujita's analysis[3]). Of 31 rated runs through W3, eight were classed as non-shears while 11 were rated as 'severe' and two as 'very severe'. Although there was about ±10% variation in shear intensity between runs, based on $\Delta U_g/\Delta h$, and about a 2:1 variation based on time or distance from touchdown, this appeared to have little effect on the ratings assigned (Fig 13a). No 'sideslip' components were identified and about one-half the runs rated as shears identified the shear content wholly correctly, while a further one-third cited a combination of U_g and W_g. It is clear that, although it is possible, in theory, to distinguish between the effects of U_g and W_g under ideal conditions, pilots have considerable difficulty in making this distinction in practice. It is interesting to note that while pilots often expressed some uncertainty regarding their assessments of shear content, in only two cases did the pilot state clearly that he was unable to distinguish between U_g and W_g. Probably of more significance operationally is the fact that about one-quarter (8) of these runs were rated as non-shears - in two cases the shear may have been masked to some extent by steep descents following non-precision approaches; the remaining six all showed significant power increases (three by auto-throttle, three manual) at the appropriate stages of the approach and the failure to associate this activity with a shear of 'Kennedy' proportions is surprising, particularly since none of these events occurred on first sorties, but it illustrates clearly the semantic problems involved. During one auto-landing P1

commented on a smaller outburst of throttle activity that occurred earlier in the approach, but <u>not</u> on the shear-induced activity!

The front W4 was dominated by lateral shear (V_g) and can probably be regarded as a single-component shear for most practical purposes. For an aircraft approaching with wings level, on the extended centre-line, the heading would have had to be changed by about 10° as the front was traversed. As can be seen from Table 1, six ratings of 'no shear' were recorded out of a total of 31: in two of these cases pilots commented on a "marked change of wind with altitude" and in a third the situation may have been confused by the need to correct a large lateral offset following a non-precision approach. Of the runs rated as shears (Table 2), in roughly one-half (13) the shear content was identified 'correctly' as V_g, while in a further quarter (6) an additional component was specified (ie UV, VW or UVW were cited): in a final group (6) V_g was not identified at all and while the true situation may have been obscured by other factors in one of these, it is difficult to see how, in the other cases, the seemingly obvious could have been mis-identified. The variation in shear intensity ($\Delta V_g/\Delta x$) between runs was rather less for W4 than for W3 and the ratings showed a slight tendency to become more severe as the shear intensified (Fig 13(b)).

Pilots were less successful at identifying the components of wind shear than they were at recognising its presence. This seems neither particularly surprising (at least so far as confusions between U and W are concerned) nor particularly important since, in the main and in the longer term, pilots' reactions to the shear were 'correct' (see later).

3.3 <u>Cues</u>

Responses to the question "What instrument or other clues made you aware of the (wind shear) problem?", posed after each run have been summarised in terms of the number of occasions on which a particular cue was cited, subdivided in various ways - Table 3 shows the distribution in terms of the type of shear (or non-shear) experienced while Table 4 shows the distribution in terms of the shear components cited by the pilot.

Before proceeding to a more detailed discussion of these results it should be pointed out that although it was not unusual for a single cue to be cited in isolation it was more usual for citations to refer to pairs or triplets of cues, at least for those runs that were correctly recognised as containing shears.

Interestingly, this distribution changed in the case of non-shears incorrectly identified as shears, to a preponderance of single-cue citations:

No. of cues cited	Shears	Non-shears
1	32	34
2	80	26
3	57	10
4	27	2
5	6	1
6	1	-

Statistically there was a highly significant association between the citation of a single cue and the incorrect assessment of a 'non-shear'. The chances of an assessment of the presence of shear being correct when based on a single cue were only around 50% - this may be an extension of those problems associated with fixation on a single source of information. When two or more cues were cited the success rate in assessing the presence of shear rose to about 82%.

Returning now to Tables 3 and 4, it is clear that the external visual field was the most frequently-cited cue, though in the conditions of the experiment this came as no surprise. This was followed by the PAPI with 127 citations and the ASI with 120. Rather surprisingly the 'RPM' cue was ranked next (63) and the list of major cues closed with VSI (50), Drift (42) and ILS (40, 19 of which referred specifically to indicated glide-path error (G/P)). Clearly some of the minor cues could have been grouped under one or other of the major headings, but they are shown in the Tables as they were recorded at the time.

In passing it may be noted that Table 4 shows evidence either of occasional misunderstanding by some pilots, or of mis-recording - eg, no PAPI, VSI or RPM indications could enable a pilot to infer the presence of a cross-wind shear in isolation, yet these cues were cited 5, 2 and 4 times respectively.

Looking further into the unexpectedly high ranking of the RPM cue showed a significant association of the cue with Automatic Approaches (A2) and Landings (A1), taken together. Furthermore, the association was reinforced if citations of the 'Auto-throttle' cue were included with citations of RPM. It seems probable that the RPM cue cited in Auto Approach/Land cases (A1, A2) may have related, in fact, to observations of auto-throttle activity*. In wholly manual

* Note that 'RPM' was one of the cues specifically listed in the questionnaire and may have been seen as a 'preferred answer'. 'Auto-throttle' had to be volunteered specially under the heading of 'Other cues'.

approaches (A3, A4), citations of the RPM cue may have arisen where it was observed that more thrust than that appropriate to the surface wind was needed to maintain the glide-path at height, thus giving the pilot early warning of possible impending shears.

A detailed study was made of possible associations, positive or negative, between particular components of shear and the citation of particular cues or combinations of cues. Many of the associations established seemed obvious to the point of triteness and are not discussed further. However, the highly significant association found between citation of the PAPI cue on the one hand and assessments of UW or W on the other suggested that this cue, with its compelling indication of vertical departure from the correct glide-path, tended to be interpreted as showing the presence of vertical draughts: it should be noted, therefore, that of the 90 occasions on which a citation of the PAPI cue was accompanied by an assessment involving vertical wind components, the inclusion of the latter was incorrect in 35 cases. It was found that citation of the PAPI cue alone was associated with incorrect assessments involving W at the 'probably significant' level: by contrast, when the PAPI was cited in conjunction with some other cue the combination had a significant association with correct assessments involving W, though the proportion of incorrect assessments was still quite high (0.36).

There were 17 cases in which pilots failed to identify the vertical component present in storms. It was interesting to observe that the Drift cue, which was cited in six of these, was associated at a significant level with such failures; furthermore, five of the six related to storm W7 in which the horizontal shear was dominated by the lateral component and the accompanying assessments were all either V or UV. It seems reasonable to suppose that pilots' attention was saturated by the evidence of a marked lateral shear and that they failed to note the other cues available in reaching their assessments (though their reactions in terms of aircraft handling usually were 'correct').

3.4 Pilot reaction and performance

In discussing the pilots' reactions to and performance during the various shear encounters it has proved useful occasionally to refer to the frequency of overshoots. It is necessary before doing this to draw attention to a disparity between the background experience of two groups in our pilot population which seems to have had an important influence on this factor. The disparity divided the British Airways pilots (plus the CAA pilot), who were relatively familiar

with the non-precision approach technique used (ADF), from the Service pilots, who were not. Since non-precision approaches are, in any event, a more demanding task, some degree of mismanagement occurred relatively more frequently among the Service pilots during these approaches; this occasionally left the aircraft badly positioned at break-out - sometimes to the point where the corrective manoeuvres required may have obscured any shear that might have been present, and sometimes to a degree sufficient to persuade the pilot to overshoot.

The distribution of overshoots, shown in Table 5, reflects these differences clearly. Note that the frequency of overshoots did not differ significantly between ADF and precision approaches for the Airline pilots, whereas the difference was very highly significant for the Service pilots. To put the matter in a different way, we may note that although the frequency of overshoots in precision approaches was slightly higher for Service pilots (at 0.082) than for Airline pilots (at 0.057) the difference was not statistically significant; for ADF approaches, however, the difference was highly significant (the frequency being 0.253 for Service pilots compared with 0.034 for Airline). Although a closer examination of the data showed an unusually large number of overshoots had been contributed by a single Service pilot (ten overshoots in 30 runs), excluding this atypical group from consideration, as indicated in Table 5, did not affect the significance of the above conclusion regarding ADF approaches, though it did reduce the difference between Service pilots (where the frequency of overshoots fell to 0.071) and Airline pilots in precision approaches to a still less significant level.

3.4.1 Pilot reaction to the 'forecast'

The weather statements made at the start of each approach could, as in 'real life', give the pilot useful clues as to the likelihood of encountering shear provided, of course, that the statements were reliable. In this section we shall examine the extent to which this information influenced approach planning and execution.

'Pro-shear' weather statements, as described earlier, were made in the case of 254 runs, and of these 141 related to runs that actually contained shear. 'Pro-shear' statements, usually of the more emotive sort, were associated with 89 of the 94 runs made through storms; the remaining five runs (all through W7) were associated with neutral or mildly negative statements.

Following strongly 'pro-shear' statements, there were 11 cases where pilots indicated that they would have diverted, held, or requested another runway in

real life. These 'pro-shear' statements were accompanied by reference to tail-winds (usually gusty) on the surface and were representatives of four classes (two of 15 runs each and two of 16 runs each) that were applied only to storm encounters. In seven of the 11 cases the pilots' comments (re diversion, etc) were volunteered by one or other of the two pilots who made nine sorties apiece, and they may well represent a 'learned' response to some extent. Moreover, nine of the 11 runs terminated in crashes or overshoots - a proportion significantly higher than that which applied to the group of storms as a whole, which in turn raises questions of the possible influence of hindsight on these comments.

In 90 cases following a 'pro-shear' weather statement the pilot announced an increase in approach speed, usually by 5 or 10 kn, and at least one such increase was made for each of the 20 categories of 'pro-shear' statement. It was observed that the frequency with which increases in approach speed were announced rose significantly (to 24 in 50) when the 'pro-shear' statements were accompanied by statements that the surface wind was 'high' (ie, total wind $\geqslant 25$ kn and/or a cross-wind component $\geqslant 15$ kn): in fact, this frequency differed little from that observed when forecasts of 'high winds' were <u>not</u> accompanied by 'pro-shear' statements (27 in 50), which might suggest that the stated surface wind provided the more potent stimulus to increase the approach speed.

There were 21 cases where the pilot selected a higher-than-normal approach speed in the absence of either a 'pro-shear' statement or a statement of high surface wind. In seven of these the pilot gave the disparity between the drift encountered at height and the stated surface wind as his main reason for the decision, and this may have been a factor in a further five cases where no reason was given - most pilots were alert to the usefulness of differences between the wind at height and on the surface as a clue to the existence of a shear line somewhere along the approach path, and disparities in drift provided the clearest and most unmistakable indication of this. (Pilots were much less successful in attempting to determine disparities in the along-track component, eg, by calculating ground-speed from rate-of-descent on a 3° glide-path, though their attempts to do so indicated that reliable information on ground-speed (eg, from an inertial navigation system) would be used and might be useful.) Wind velocities of 120/10 or 240/10 (ie, quartering tailwinds) at the surface were forecast for eight cases and provided the only other common feature noted in this group of 21; however the frequency of occurrence (8 in 36) shows this to have been a much less potent stimulus than either 'pro-shear' or 'high wind' statements.

3.4.2 Pilot reaction to the shear

In the following discussion the various types of shear have been treated in separate sub-sections, each being further sub-divided by approach type and, where appropriate, by whether or not the presence of shear was identified. We shall discuss the repertoire of pilot responses and seek to distinguish the more successful.

(a) Abnormal boundary layer (W1)

Of the (13) runs wrongly identified as non-shears, three occurred during scheduled auto-lands that were continued to touchdown and one occurred during recovery from a large offset following a non-precision approach which obscured the record of any pilot reaction that may have occurred: in the remaining (9) cases no pilot reaction was discernible.

Of the (17) runs correctly identified as shears, two occurred during auto-lands, both of which were continued to touchdown. There were seven cases where the pilot made substantial adjustments of thrust - though two of these were associated with late corrections to mis-managed ADF approaches - and there were two cases that did not involve thrust changes, where the rotation in the flare was notably larger than usual. In the remaining (6) cases the records showed no evidence of pilot reaction to the shear: this was a notably lower proportion than that observed in the cases incorrectly identified as non-shears.

(b) Low-level jets (W2, W3)

Of the (16) mis-identified runs, two occurred during auto-lands, both of which were continued to touchdown, and five during mis-managed ADF approaches where the record of any pilot reaction to the shear was obscured by the manoeuvres made to regain the glide-path: in the remaining (9) cases, appropriate control inputs were recorded during the shear encounter.

Seven runs identified as shears occurred during approaches scheduled as full auto-lands (A1): two of these were continued to touchdown, four were landed entirely manually and one was landed by the auto-pilot with manual operation of the throttle. This large reduction in the proportion of auto-lands that were continued to touchdown was the only significant difference observed from the cases wrongly identified as non-shears. A typical response of the auto-land system is illustrated in Fig 14.

Encounters that occurred during auto ILS/manual landings (A2) showed no significant difference between those that were correctly identified as shears (16)

and those that were not (3). In the most commonly used strategy (9 runs) the auto-throttle was disengaged during its response to the decreasing headwind, usually shortly after reaching its maximum authority, and this usually was accompanied (or followed closely) by a pilot-commanded increase in thrust, the auto-pilot being left engaged down to around normal decision height (200 ft). On two occasions the auto-throttle was disengaged during the headwind increase (ie while the throttles were closing), the auto-pilot remaining engaged down to decision height. The auto-pilot and auto-throttle were disengaged more-or-less simultaneously on seven occasions - three being markedly late, which allowed the automatics to deal with virtually the entire encounter. There was one auto-throttle malfunction and disengagement before the onset of the shear.

Four encounters identified as shears took place during non-precision approaches (A4). In two the combined problems induced the pilot to overshoot, while the remaining two showed response features broadly similar to those described below for manual ILS approaches.

Encounters that occurred during manual ILS approaches (A3) showed no significant difference in response between runs that were identified as shears (18) and those that were not (5): the following discussion therefore applies to the whole group. It was notable that pilots appeared reluctant to throttle back during the phase where headwind was increasing and rarely did so to the same degree as the auto-throttle, (see Fig 14 for example) consequently the aircraft had gained energy relative to normal (usually in the form of excess height) at the point where the shear changed sign: the extent to which this was part of a deliberate strategy is not clear, though it is consistent with traditional wisdom. Pilots reacted to the subsequent negative shear by increasing thrust and raising the nose: the delay between the change of sign of the shear and the first significant opening of the throttle is shown in histogram form in Fig 15. There were no significant differences observable between the two shears and the overall average reaction time was 4.9 s with a standard deviation of 2.4 s. The only overshoot in this group followed an unusually long response time (11.7 s).

The average of pilot reaction times (as defined above) in automatic approaches in which the auto-throttle was disengaged early was notably lower (about 3.4 s) than in manual approaches. This tends to confirm that auto-throttle movement acted as a stimulus to pilot action on some occasions.

Pilots usually exhibited no difficulty in dealing with the modest cross-wind component of shear W2, though it was noted that the few pilots who, during

this simulation, showed a tendency toward lateral pilot-induced oscillations (PIO) had this tendency activated by the encounter.

(c) Fronts (W4, W5)

Of the (12) mis-identified encounters, two occurred during auto-lands both of which were continued to touchdown, two during recovery from mis-managed ADF approaches and the remainder showed appropriate control inputs by the pilot during the encounter (but see below for further comment). Thus, as noted earlier for W2, W3, in all cases where pilot reaction was not obscured by other factors the occurrence of shear led to a (more or less) appropriate response, even when it did not lead to a rating.

The auto-pilot was quite capable of dealing with these shears and since the latter ceased at about 200 ft the optimum strategy was to "leave it to George": this strategy was followed in nine out of ten auto-lands (A1) and in 17 out of 21 coupled approaches (A2).

It was particularly interesting to observe that in eight of the 20 encounters that occurred during manual ILS approaches (A3) the pilots' initial application of aileron was in the 'wrong' sense (ie, in the sense to re-inforce the shear-induced roll rate); this may also have occurred in a further three cases where the initial conditions were obscured by other factors. The reasons for this reaction are not clear, though they may be associated with the initial response of the (uncontrolled) aircraft to the cross-wind shear (yaw to port, roll to starboard) which, considered only in terms of apparent displacement of the runway lights within the windscreen frame, might be interpreted as a translation of the aircraft to port, calling for starboard bank to regain the centre-line. The absence of peripheral cues (eg lights on other runways, in nearby buildings, or on roadways, etc) may have contributed to the illusion - certainly it provoked complaints from some pilots. Whatever its cause, this 'incorrect' reaction usually involved only small aileron inputs and was quickly corrected (usually in about 2 s); however, in four of the eight cases, it was followed by some degree of lateral PIO; in the ten cases where the initial reaction was not 'incorrect' in this sense there was only one occurrence of a lateral PIO. An encounter illustrating this 'incorrect' initial response and the subsequent PIO is shown in the time-history of Fig 16.

Longitudinal control activity in response to fronts usually was slight - indeed in five cases the thrust was not altered significantly throughout the encounter - however, in a few instances substantial increases in thrust were made,

usually rather late in the encounter, perhaps in anticipation of an associated longitudinal or vertical shear that failed to materialise. At least one overshoot of the three made from manual ILS approaches seems to have been triggered by unnecessary throttle activity of this sort, that left the aircraft too high (and offset laterally) too close to the threshold; the single overshoot off a coupled ILS approach seems to have arisen in a similar way.

There were ten encounters with fronts during non-precision approaches. The increased difficulties of this type of approach made for greatly increased lateral control activity in all cases, but particularly when combined, as here, with a cross-wind shear: this increase was often but not always accompanied by increased longitudinal control activity. In four cases these problems aggravated by poor positioning at breakout, induced the pilot to overshoot.

(d) Storms (W6, W7, W8)

Of 83 encounters in this group 14 were scheduled as full auto-lands (A1). Only one of these was allowed to continue to touchdown without interruption and one other was landed by the auto-pilot, the throttle being controlled manually. All the remainder reverted to full manual control at some stage of the encounter. Examination of the responses in these reversionary cases showed that they were technically little different from those made during auto-approach/manual landings (A2) and we have therefore treated the two groups together below.

In 18 cases the auto-pilot and auto-throttle were disconnected more-or-less simultaneously and in a further 16 cases the auto-pilot was disconnected after the auto-throttle by intervals that ranged from 1 s to 8 s (average 3 s): in only one case was the auto-pilot disconnected first. Relative to the normal decision height for A2 (200 ft) auto-pilot disconnection occurred high (ie at or above 220 ft) in 21 cases, close to decision height (ie from 190 to 210 ft) in 14 cases and low (below 180 ft) in two cases, one a scheduled auto-land.

For storms on the extended centre-line (W6, W8) the auto-throttle was disconnected shortly after it had reached full authority (average 5 s) in all cases. Disconnection was accompanied by a simultaneous, pilot-commanded increase in thrust on nine occasions, while on the remaining 15 occasions the thrust increase was somewhat delayed (average 2.7 s). The pattern was somewhat different for offset storms (W7) in that the auto-throttle was disconnected before reaching the limit of its authority on five occasions, disconnection being accompanied by a thrust increase in each case: in the remaining ten cases the average interval between the auto-throttle reaching full authority and being disconnected was

somewhat shorter (4.2 s) than for the symmetrically-placed storms, moreover disconnection was accompanied by a simultaneous thrust increase in nine of the ten cases. The earlier responses provoked by W7 suggest that pilots may have been alerted to the possibility of shear by the discrepancy between the wind at height and the reported surface wind and, perhaps more importantly, by the intensifying cross-wind observable from the moment they 'went visual' - well before the main longitudinal disturbance.

Although their response was contaminated to some extent by the nose-up trim change on auto-pilot disconnection, pilots generally raised the nose on reverting to manual and accepted the consequent losses in airspeed down to operation of the stall-warning.

An example of an encounter with storm W8 during a coupled approach (A2) is shown in Fig 17. It illustrates many of the features that have been described above and also shows some degree of over-controlling in pitch following auto-pilot disengagement.

Encounters with storms during manual approaches (A3, A4) provoked responses that were broadly similar to the coupled approaches in that pilots invariably increased thrust and, in all but two or three cases, raised the nose. In these exceptional cases the nose was lowered deliberately in an attempt to retain or regain airspeed, accepting that the aircraft might descend below the safety trace (defined in these experiments as a line extending upward from the threshold at 1.8° to the horizontal), which, in the circumstances of these experiments, was not of practical importance: the strategy was successful in that by 'going low' the aircraft tended to encounter less intense downdraughts, but in real life it may be useful only as a last resort.

Since the degree of success in coping with storms seemed to depend very much on timing, particularly of thrust inputs, we turn now to examine this. It was convenient to measure response times from the moment at which the downdraught first reached 10 ft/s to the moment at which the thrust first reached the maximum authority of the auto-throttle, thus facilitating comparisons between the automatic and human pilots. Histograms of these response times are shown in Fig 18 for automatic and manual ILS approaches.

It will be noted that the automatic approaches (A1, A2) exhibited marked differences in 'response time' between the three classes of storm. These differences had their origins in the different velocity fields of each group; in particular, the negative shift in the 'response time' of W8 compared with W6 appears to

be a consequence of the greater shear of longitudinal wind in the former case (see Fig 10) operating via the error rate term in the auto-throttle. The intra-group variability, which must have been caused by random variations in turbulence, or in the shear field, or in auto-pilot performance, seemed surprisingly large.

For the manual ILS approaches the intra-group variability was, as might be expected, significantly larger - the standard deviation of 'response time' was typically about twice that obtained during automatic approaches. More importantly, it was observed that infringements of the safety trace occurred only in those cases where the 'response time' was above (usually well above) the average for a particular group. No infringements were associated with manual ILS approaches through storms W7 and it may be that this was partly a consequence of the 'early warning' offered by the obvious discrepancy between the cross-wind component observed at height and the reported surface wind: note also that the average manual response time associated with this shear (W7) was some 2 s less than that observed for coupled approaches, a unique feature which, again, may have been due partly to the 'early warning' available. These observations re-emphasise (if emphasis is needed) the importance of an early and appropriate response to wind shear, ie the pilot must be quick to counter the energy-sapping effects of the shear by applying thrust.

3.4.3 Performance

The aircraft touched down short of the threshold on nine occasions, all of which followed storm encounters. Two of these 'crashes' seem to have been the consequence of computer malfunctions as noted earlier: the remaining seven were all associated with the exceptionally severe shear of storm W8A and some of these may also have entailed computer malfunctions. If encounters with W8A are dismissed from consideration the overall success rate (in terms of avoiding crashes) was surprisingly high, though, or course all the participants in these experiments were highly motivated and were aware that they were likely to encounter several shears per sortie: moreover the aircraft had relatively high performance capability.

Turning to a more discriminating criterion, the infringement of the 'safety trace', it was noted that this occurred on 12 occasions (excluding crashes and shear W8A): ten of these followed storm encounters (4 W6; 1 W7; 5 W8), one followed the abnormal boundary layer (W1), while one followed a 'non-shear' and seems to have been 'self-inflicted'. Seven infringements occurred during or were followed by overshoots (1 W1; 2 W6; 1 W7; 3 W8).

It is interesting to observe that the frequency of occurrence of 'infringements' did not differ significantly following storms W6 or W8 but was significantly lower following storm W7. A possible explanation of these differences has been discussed in earlier sections.

Although successful overshoots were regarded as a perfectly satisfactory outcome to a shear encounter and pilots were briefed to overshoot if they felt at all doubtful of accomplishing a successful landing, overshoots occurred relatively infrequently and their occurrence seemed to be related to task difficulty. In Table 5, for example, the combined overall frequency of overshoots (excluding the data contributed by Pilot I, which was atypical) can be seen to increase as the task became more difficult, eg in progressing from A1 to A4, though the observed differences proved not to be statistically significant. The majority of overshoots followed storm encounters, which undoubtedly were the most demanding shears, and within the group of storms the ratio of successful landings to overshoots reduced through the sequence A2, A3, A4, though again not to a statistically significant degree. Interestingly the overshoot-landing ratio for scheduled auto-lands that reverted to manual in storms (7:3) was notably higher than that observed in the technically-similar case of auto-approach/manual landing (8:18), which suggests that a decision to make an unscheduled disengagement of the auto-land system may have predisposed the pilot to a subsequent decision to overshoot.

The majority of shear encounters ended in relatively normal landings and it seemed appropriate to enquire whether these could be classified in terms of their quantitative effects on the approach and landing performance, compared with the performance in the absence of shear. There are, of course, many potential indicators of this sort and a few of these are discussed below.

Departures from the target rate of descent (670 ft/min at the standard approach speed of 125 kn, on a 3° glide-path in still air) might be expected to reflect the degree of difficulty especially when they occurred late in the approach. Quite arbitrarily we have chosen a rate-of-descent of 1200 ft/min when below 300 ft as indicating a fairly severe degree of difficulty. This condition was exceeded on a total of 154 runs (excluding three that were associated with shear W8A) which can be grouped as shown in Table 6. Note that here again it has been necessary to differentiate between non-precision approaches and the rest - in 'non-shear' conditions high rates of descent occurred ten times more frequently for non-precision approaches (0.55, compared with 0.0545) though

there was no significant difference here between Service and British Airways pilots, which contrasts with the difference observed in overshoot frequencies for non-precision approaches (which, in turn, may suggest that BA pilots were less willing to overshoot).

Taken overall there was no significant difference due to shear in the frequency of occurrence of high descent rates in non-precision approaches. By contrast it was found in precision approaches that even the least potent group of shears (which, in this context, proved to be the fronts W4 and W5) resulted in a highly significant increase in the frequency of high descent rates when compared with 'non-shear' conditions: moreover, there were significant differences in frequency between classes of shears which showed only small intra-group differences - for example between the low-level jets (W2 and W3) and the fronts (W4 and W5). Furthermore there were differences in frequency associated with sub-classes within the group of storms, those between W6 on the one hand and W7 or W8 on the other, being 'significant', while those between W7 and W8 were 'highly significant'.

The frequency of occurrence of 'severe' or worse ratings has been plotted against the frequency of occurrence of excessive descent rates ($\dot{h} \geqslant 1200$ ft/min) for precision approaches and it can be seen (Fig 19) that the points fall within a fan-shaped region having its apex at the origin and that its upper bound is defined by shears W5 and W7 (and, to a lesser degree, W4), that is to say by those shears involving large changes of cross-wind. The slope of the upper bound is roughly three times that of the lower, or roughly twice that of the line defined by shears W6 and W8 - that is to say, in the latter case, that for a given level of 'severity' excessive descent rates occurred only half as often in the conditions associated with the upper bound. We believe this to have been a consequence of the readily detectable 'early warning' provided by those conditions.

High rate of descent at touchdown might also be expected to reflect the difficulty encountered during a particular approach and we have chosen, arbitrarily, to regard rates exceeding 600 ft/min as 'high'. Such exceedances occurred on only 28 occasions, distributed as shown in Table 7 where, once more, we have found it necessary to differentiate between precision and non-precision approaches since heavy landings occurred significantly more frequently in the latter class. For both classes of approach, heavy landings occurred significantly more frequently when shear was present and were particularly closely associated

with the abnormal boundary layer, W1 (frequency of occurrence 0.3 for precision, 0.67 for non-precision approaches), and the storm W6 (frequency of occurrence 0.2 for precision, 0.67 for non-precision approaches). The reason for this was clear in the case of the abnormal boundary layer, W1, being simply the rapid decay of head-wind (and hence airspeed) close to the ground: we are unable to offer an explanation for the association in the case of storm W6 in the absence of a corresponding association with storm W8, which it closely resembled - indeed the gradient of head-wind was more severe in the case of W8 (see Fig 10).

Landing performance expressed in terms of the position and rate of descent at touchdown is shown in Fig 20 and Table 8a for approaches made in the absence of intentional shear*. The data have been grouped by the type of boundary layer encountered and by the approach technique. Differences in the form of the boundary layer had a significant effect on the touchdown positioning achieved during automatic landings (A1) and, apparently, on the rate-of-descent at touchdown following non-precision approaches (A4): the former were attributable to and consistent with the control laws of the automatic system but no explanation could be found for the differences observed with A4. The form of the boundary layer had no significant effect on touchdown performance in either automatic (A2) or manual (A3) ILS approaches. Moreover, the differences in touchdown performance between automatic and manual ILS were not statistically significant.

More detailed analysis of the touchdown performance achieved on 'non-shear' approaches showed there were significant differences statistically between various pilot groups and that these differences appeared to depend on the combination of boundary layer type and approach aid. The matter was not developed further as it was evident that an additional sub-division of the data (by pilot group) would lead to undesirably small samples when the effects of shear came to be studied.

Some features of the landing performance in the presence of shear have been summarised in Table 8b. It was observed during the analysis that differences between the two examples of low-level jet (W2 and W3) and between the two examples of front (W4 and W5) were not significant and these data have therefore been combined for presentation in the Table.

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* The data shown relate only to runs correctly identified as non-shears. There were significant differences of landing performance in the runs 'incorrectly' identified as shears for manual ILS approaches.

It will be observed that the abnormal boundary layer (W1) resulted in touchdown points that were significantly closer to the threshold for all approach techniques (compared with 'non-shear' conditions) and rates of descent that were significantly higher for all but the non-precision approaches. Moreover the dispersion of touchdown position was significantly reduced by the shear, again with the exception of A4 (where it increased). So far as the precision-approach techniques are concerned these findings were wholly consistent with this type of shear, indicating, as suggested earlier, that neither the human nor the automatic pilot had the capacity wholly to counter its effects in the short time available. The results for the non-precision approaches present a more confused picture which may be partly a consequence of the lack of familiarity of some of the pilots with this procedure.

Rates of descent at touchdown for automatic landings were significantly higher in the presence of fronts (W4, W5) or low-level jets (W2, W3) than they were under non-shear conditions, as were the dispersions of touchdown points. Mean touchdown points were significantly closer to the threshold for the fronts, compared with non-shear conditions. More surprisingly, the presence of fronts or jets had few significant effects on the landing performance achieved from any type of manaul or semi-manual approach.

Although some of the storm/approach groupings comprised undesirably small samples it is clear from Table 8b that the mean touchdown distance from the threshold was significantly greater in all cases compared with 'non-shear' conditions - the factor typically being about 1.5 - and in most cases this was accompanied by a significant increase in dispersion. Apart from this, storms W7 and W8 resulted in no significant differences in the indicators of landing performance considered here. By contrast, storm W6 led to significantly higher rates of descent at touchdown.

It seems clear that the 'long' landings associated with storms arose because pilots, having increased thrust in response to the downdraught/wind shear, were reluctant to reduce it until convinced that it was safe to do so* - an understandable (and indeed laudable) reaction in the circumstances, though capable of introducing new dangers if carried too far.

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* The example shown in Fig 17 is atypical in this respect.

The higher-than-normal rates of descent at touchdown associated with storm W6 are allied with the relatively high frequency of 'heavy' landings referred to earlier: the reasons why these phenomena should have occurred with W6 but not with W8 are not properly understood.

Two subjects acted as pilot-in-command on nine sorties apiece and a further two on five sorties apiece. There was no evidence from these cases of a significant consistent variation in any criterion of touchdown performance with accumulating experience. However, many of the pilots were convinced that they had benefitted by participating in these experiments and would be better equipped to cope with wind shears in real life as a consequence.

3.4.4 Oscillatory control inputs

This section is in many ways something of an aside, though the observations it contains have some bearing on the quality of the simulation.

Longitudinal

Oscillatory inputs to the longitudinal control were clearly discernible on 221 runs and in the majority of cases these were of the type that have come to be known as 'elevator pumping'[4], that is to say, a brief episode during the flare of cyclic inputs, usually of increasing amplitude, the maximum occurring shortly before touchdown: in 179 episodes the oscillatory phase lasted for five cycles or less. There were seven cases in which the oscillatory phase lasted for ten cycles or more and in all these the amplitude remained roughly constant for much of the time but increased over the last two or three cycles, giving the impression of a small-amplitude limit-cycle PIO leading into an episode of 'stick pumping'. The remaining 35 cases were intermediate between these two forms (eg see Fig 17).

All pilots contributed examples of oscillatory inputs though the frequency of occurrence varied widely between individuals (from about 20% to 70% of the approaches made). The average frequency of occurrence was about 40% of all approaches and this did not vary significantly with the presence or absence of shear. However, when the comparison was based on the number of landings rather than approaches the frequency of occurrence was found to be slightly higher in the presence of shear (at 0.44, compared with 0.36 in its absence) - a difference significant at the 5% level, and one that might reflect a slightly higher residual stress level in the pilot following shear encounters. The fact that episodes of 'stick pumping' occurred in a manner comparable to that observed in

flight can be considered as supporting the validity of the longitudinal aspect of the simulation.

The period of the input varied somewhat between pilots and from run to run, but usually fell within the range 2-3.5 s, the overall average being 2.79 s. In a few cases of relatively long duration it was observed that the input period decreased slightly with time (ie as the height decreased). Input amplitudes over the near-constant part of the longer-duration events were typically around $\pm 2^{\circ}$ of elevator, the corresponding output amplitudes being in the region of $\pm 1^{\circ}$ in pitch attitude and ±0.05 g in normal acceleration.

In a few cases it was possible to detect 'by eye' evidence of cyclic inputs of much longer period than those described above (eg 8 s and 12 s) which seem to have been a response to failure to establish a well-stabilised approach condition.

Lateral

Although oscillatory lateral inputs occurred less frequently than longitudinal they were, in fact, recorded on 82 runs and occurred in isolation on 24 of these. The majority (73) of these inputs had periods similar to the longitudinal, the average being 3.05 s, but they differed, firstly, in occurring rather earlier in the approach (typically, pre-flare) and, secondly, in being much larger in amplitude (aileron inputs usually were between $\pm 5^{\circ}$ and $\pm 10^{\circ}$).

There were four cases where periods of 15 s were observed and a further five where the period ranged from 5 s to 11 s. All these involved substantial excursions in bank, heading and track and appeared to be triggered by overcorrection of an initial track/heading error.

These aspects of the lateral behaviour would not normally be observed to the same extent, if at all, in experienced pilots in actual flight and are believed, therefore, to be an artefact of the simulation. They are consistent with adverse comments by pilots on the lateral handling/presentation and specifically with those directed at the absence of peripheral visual cues, though other shortcomings may also have contributed to the problem. It is worth noting that the liability to lateral PIOs varied widely between pilots; moreover, there was evidence suggesting that a high liability decreased as experience of the simulation increased.

4 CONCLUSIONS

(1) It was clear that pilots were usually successful in recognising the absence of shear (about 80% success) or the presence of severe shear, such as might be met near a thunderstorm (100% success), but were less successful in recognising shears of more moderate intensity or which occurred late in the approach. However, the presence of shear usually was acknowledged implicitly by appropriate corrective action even when the shear failed to meet the definition used by a particular pilot and so was not identified explicitly.

(2) Pilots were less successful in identifying the velocity components present in a particular shear encounter and were notably prone to discern vertical draughts where none existed - a tendency that increased as the shear became more intense in the pilots' assessment. It became clear that pilots had great difficulty in distinguishing reliably between the effects of longitudinal wind changes and vertical draughts. However, this had little practical significance since their direct response to either phenomenon was to attempt to regain energy.

(3) The Precision Approach Path Indicator (PAPI) was the most frequently cited of the specific cues and was clearly a valuable aid in discerning shear: however, its compelling suggestion of vertical movement may also have been partly responsible for the frequent 'identification' of non-existent vertical draughts. In terms of frequency of citation the PAPI was followed closely by the ASI and, though less closely, by RPM, VSI, Drift and ILS in that order. With the exception of RPM these cues have an obvious significance. It seemed likely that some of the RPM citations related in fact to observed activity of the auto-throttle during automatic or coupled approaches.

(4) Pilots were quick to seek clues that might give 'early warning' of possible shear. The most obvious examples were to be seen where the cross-wind at height differed from the announced surface wind (as in the fronts and one storm) and these were frequently commented upon. It is believed that further examples occurred in a fair proportion of RPM citations where, it is hypothesised, the difference between the power required to maintain glide-path at height and that appropriate to the announced surface wind alerted pilots to the likelihood of shear. Pilots also attempted to deduce groundspeed from the rate of descent needed to maintain the (3^{o}) glide-path and hence, with airspeed, to deduce the longitudinal component of the wind at height and to compare this with the announced surface wind. They were less successful in this method but the fact that the attempts were made indicates the potential usefulness of reliable

information of this sort (for example, such as could be obtained from an inertial platform) when combined with reliable reporting of conditions at the surface.

(5) Weather statements that suggested shear might be encountered may have alerted pilots but did not usually persuade them to increase the approach speed unless, in addition, the surface wind was stated to be high. Pro-shear statements were no more likely to induce a higher approach speed than were statements that involved high winds alone. However, inferences regarding shear drawn from disparities between the wind at height and at the surface were often given as the reason for increasing approach speed. Clearly there are benefits to be gained from a reliable ground-based shear-warning system. It is reasonable to infer that a medium-range, airborne shear-detection system would confer even greater benefits and that its development should be actively pursued.

(6) Performance varied widely between individuals and between sub-groups of the pilot population. Few individuals underwent repeated trials: some of those that did were highly consistent performers, others were less so, but there was no significant evidence from these trials that accumulating experience had a consistent effect on overall performance. Such evidence as there was suggested that pilots coped slightly more successfully with shear in their later trials, and many pilots were convinced that they had benefitted from participation and would be better able to cope with 'real life' shears. There are good reasons, therefore, for proposing that shear encounters should be incorporated in airlines' simulator training programmes.

(7) Only two crashes occurred following designed shears and, in both, computer malfunctions were suspected. This surprisingly high success rate probably was contributed to by:

(a) the fact that all encounters took place under VMC and with good visual aids (PAPI),

(b) the relatively high performance of the simulated aircraft, and

(c) the high motivation of the participants and their awareness that they would encounter several shears per sortie.

(8) More discriminating criteria showed that 'success' followed prompt and appropriate reaction to the shear, while 'failure' was associated with late or inappropriate reaction. This emphasises again the potential advantages of means of reliably indicating to the pilot that shear is likely to be encountered: even a system that indicates the presence of shear before the overt symptoms of an encounter become apparent may be of value. 126

(9) The 'massed attack' has proved appropriate for the broad approach of the present study. Future work is likely to be aimed at specific problem areas and at potential solutions suggested by this and other studies. It will call for a more detailed approach in which the pilots' role will be a more interactive one and this, in turn, will imply a smaller population. It will be necessary in selecting participants for such future studies to bear in mind the inter-pilot variability shown in the present work.

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Appendix

QUESTIONNAIRE

(1) Was there wind shear?

(2) If so, at what height?

(3) Was the problem caused by longitudinal (U_g), lateral (V_g) or vertical (W_g) changes in wind velocity - or by some combination?

(4) How severe was the shear? (Choose from - very severe, severe, moderate, light, negligible.)

(5) What instrument or other clues made you aware of the problem? (Choose from - altimeter, ASI, groundspeed, VSI, drift, ILS (glideslope or localiser), RPM, external, other.)

(6) What remedial action did you take? (Choose from - power increase/decrease, nose raise/lower, turn left/right, change flap to X°, disengage auto-throttle, uncouple ILS, discontinue auto-land, other.)

(7) Did it work? (Choose from - correct and effective, correct, ineffective, wrong.)

(8) How would you assess overall the approach and landing task? (Choose from - very difficult, difficult, moderate, easy.)

Table 1

PILOTS' ASSESSMENTS OF INTENSITY OF SHEAR

Shear type	Rating omitted	Rated twice	Number assessed as									Total ratings	Total runs
			No shear	Negli-gible	Light	L-M	Moder-ate	M-S	Severe	S-VS	Very severe		
Flat profile	5	2	151 (85)	2 (1)	10 (5.5)	4 (2)	8 (4.5)	0 -	2 (1)	0 -	1 (0.5)	178* (100)	185
Normal boundary layer	6	2	146 (79.5)	0 -	12 (6.5)	3 (1.5)	18 (10)	1 (0.5)	1 (0.5)	1 (0.5)	2 (1)	184** (100)	190
W1	1	1	13 (42)	2 (6.5)	6 (19.5)	0 -	6 (19.5)	1 (3)	2 (6.5)	0 -	1 (3)	31 (100)	31
W2	2	1	8 (26.5)	0	2	2	13	0	2	0	3	30	31
W3	1	0	8 (26)	0	3	1	6	0	11	0	2	31	32
W4	0	1	6 (19.5)	0	3	0	12	0	7	0	3	31	30
W5	0	1	6 (18)	0	6	1	9	3	5	0	3	33	32
W6	0	0	0	0	1	0	8	1	8	1	9	28	30†
W7	1	0	0	0	0	0	8	1	9	0	13	31	32
W8	0	1	0	0	0	0	2	1	10	0	9	22	21
W8A	0	0	0	0	0	0	0	0	0	0	11	11	11

Figures in brackets denote percentage of total ratings
* Excludes 4 runs that contained unintentional shears
** Excludes 2 runs that contained unintentional shears
† Includes 2 runs that appear to have computer faults and have been omitted from the analysis

Table 2

PILOT ASSESSMENT OF SHEAR CONTENT

Pilot assessment of shear content	Flat profile	Normal B-layer	W1 UV	W2 UV	W3 U	W4 uV	W5 uV	W6 UvW	W7 uVW	W8 UVW	W8A UVW*	Total
U	11	9	8	9	11	4	5	2	2	3	-	64
V	8	9	4	2	-	13	9	1	2	-	-	48
W	7	8	2	1	2	1	-	11	3	4	3	42
UV	3	3	2	4	-	3	4	1	6	-	-	26
UW	-	5	-	5	8	1	1	9	5	10	3	47
VW	2	2	1	-	-	2	4	-	8	-	1	20
UVW	1	6	-	1	-	1	3	4	6	4	4	30
U or W	-	-	-	-	2	-	-	-	-	-	-	2
Not recorded	1	-	-	-	-	-	-	-	-	-	-	1

* Major components in capitals, minor components in lower case, eg UvW indicates v component was less significant than U or W components.

Table 3

CUES CITED BY PILOTS

	Flat profile	Normal B-layer	W1	W2	W3	W4	W5	W6	W7	W8	W8A	Total
External	18	19	9	8	13	16	19	10	19	11	8	150
PAPI	12	19	5	6	11	7	3	19	21	15	9	127
ASI	11	9	5	13	15	9	6	10	21	15	6	120
RPM	3	5	2	11	6	4	6	6	9	10	1	63
VSI	4	6	3	5	1	5	2	9	7	6	2	50
Drift	1	4	-	3	-	11	11	1	11	-	-	42
ILS (incl G/P)	2	3	2	4	1	3	3	8	7	4	3	40
Altimeter	-	2	1	2	-	1	-	-	-	1	1	
Pitch attitude	3	1	1	2	-	-	-	-	-	-	-	
Ground speed	-	-	1	1	-	-	-	1	1	-	1	
Auto-throttle	1	-	-	1	-	-	-	1	-	-	-	
Sink	-	-	-	-	-	1	-	-	1	-	-	
Float	-	-	-	-	-	1	-	-	-	-	-	44
Runway aspect	-	-	-	-	-	1	-	1	-	-	-	
Heading	1	1	1	-	-	4	1	-	-	-	-	
Yaw	-	-	-	-	-	1	1	-	-	-	-	
Line-up	1	2	-	-	-	-	-	-	-	-	-	
Off ℄	-	1	1	-	-	-	-	-	-	-	-	
Bank activity	-	1	-	-	-	-	-	-	-	-	-	
ADF	-	-	-	-	-	-	-	1	-	-	-	

PAPI Precision Approach Path Indicator
ASI Air Speed Indicator
RPM Revolutions Per Minute
VSI Vertical Speed Indicator
ILS Instrument Landing System
G/P Glide-Path
ADF Automatic Direction Finder

Table 4

CUES CITED BY PILOTS

	U	V	W	UV	UW	VW	UVW	U or W	Not recorded		Total	Cues cited
Shears	44	31	27	20	42	16	23	2	0		205	203
Non-shears	20	17	15	6	5	4	7	0	1		75	73
CUES:											Total	(Shear)
External	26	33	23	14	18	14	20	2	-		150	113
PAPI	20	5	29	12	32	10	18	1	-		127	96
ASI	35	8	9	13	29	9	15	1	1		120	100
RPM	28	4	6	6	11	4	3	-	1		63	55
VSI	5	2	9	5	14	7	7	-	1		50	40
Drift	1	19	1	9	-	7	5	-	-		42	37
ILS (incl G/P)	10	1	8	7	4	2	8	-	-		40	35
Other	9	10	5	9	4	4	3	-	-		44	31
											636	505
'OTHER' CUES												
Altimeter	2	1	2	1	1	-	1	-	-	8		
Pitch attitude	4	-	-	2	1	-	-	-	-	7		
Groundspeed	1	-	1	1	-	1	1	-	-	5		
Auto-throttle	1	-	1	-	1	-	-	-	-	3		
Sink	-	1	1	-	-	-	-	-	-	2		
Float	1	-	-	-	-	-	-	-	-	1	44	
R/W aspect	-	-	-	-	1	-	1	-	-	2		
Heading	-	4	-	3	-	1	-	-	-	8		
Yaw	-	-	-	-	-	2	-	-	-	2		
Line-up	-	1	-	1	-	-	-	-	-	2		
Off ℄	-	2	-	-	-	-	-	-	-	2		
Bank activity	-	1	-	-	-	-	-	-	-	1		
ADF	-	-	-	1	-	-	-	-	-	1		

Table 5

DISTRIBUTION OF OVERSHOOTS

Approach type	Pilot group	Non-shear		Shear type									Total over-shoot	Total runs
		FP	NBL	W1	W2	W3	W4	W5	W6	W7	W8	W8A		
A1	A	0	0	0	0	0	0	0	0	0	1	0	1	28
	S	0	0	0	0	0	0	0	2	3(2)	1(0)	0	6(4)	71(65)
A2	A	0	0	0	0	0	0	0	1	0	1	2	4	57
	S	0	0	1	0	0	1	0	2	3(2)	1	1	9(8)	151(142)
A3	A	0	0	0	0	0	0	0	0	2	1	0	3	57
	S	1	0	1	0	1(0)	1	2	3	3(2)	4(3)	0	16(13)	154(145)
A4	A	0	0	0	0	0	0	0	0	1	0	0	1	28
	S	1(0)	3	0	3	1(0)	2	2(1)	2	3	2(1)	0	19(15)	76(70)
All non-ADF	A	0	0	0	0	0	0	0	1	2	3	2	8	142
	S	1	0	2	0	1(0)	2	2	7	9(6)	6(4)	1	31(25)	376(352)

A1 Full auto-land
A2 Auto approach, manual landing
A3 Manual ILS and landing
A4 ADF

A Airline (includes CAA pilot)
S Service

Figures in brackets denote totals excluding Pilot I

Table 6

NUMBER OF OCCASIONS ON WHICH RATE OF DESCENT ≥ 1200 ft/min BELOW 300 ft
TOTAL RUNS IN SAME CATEGORY

	Non-shear			Shear								
	Flat profile	Normal BL	Total	W1	W2	W3	W4	W5	W6	W7	W8	Total
Precision approaches	8/154	9/158	17/312	6/25	10/26	11/27	5/25	4/27	17/23	12/27	18/18	83/198
ADF	20/31	15/32	35/63	2/6	0/5	1/5	2/5	4/5	3/5	4/5	3/3	19/39

Table 7

NUMBER OF OCCASIONS ON WHICH RATE OF DESCENT ≥ 600 ft/min AT TOUCHDOWN
TOTAL TOUCHDOWNS IN SAME CATEGORY

	Non-shear			Shear								
	Flat profile	Normal BL	Total	W1	W2	W3	W4	W5	W6	W7	W8	Total
Precision approaches	2/153	1/158	3/311	7/23	1/26	1/26	1/23	0/25	3/15	0/16	1/9	14/163
ADF	1/30	4/29	5/59	4/6	0/2	0/4	0/3	0/3	2/3	0/1	0/1	6/23

Table 8a

TOUCHDOWN PERFORMANCE - NON-SHEARS (RATED AS NON-SHEARS)

		A1*			A2*			A3			A4		
		x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)
Flat profile	Sample	26	26	26	58	58	60	41	41	41	23	23	24
	Mean	1292	1.33	2.90	1413	2.09	4.87	1549	6.00	5.12	1395	2.14	4.51
	σ	241.2	3.37	1.20	485.7	20.6	1.89	484.5	22.5	2.07	358.6	27.1	1.89
Normal BL	Sample	20	21	21	45	50	50	47	47	48	24	25	25
	Mean	1411.5	5.42	2.71	1489	-1.17	4.78	1551	3.97	5.07	1440	-5.36	6.17
	σ	339.9	5.42	0.94	503.4	21.08	1.58	468.3	21.59	1.66	509.8	17.74	2.65

* Auto-lands (A1) that reverted to manual have been included under auto approach/manual landing (A2) (6 FP: 2 NBL)

Table 8b

TOUCHDOWN PERFORMANCE - SHEARS

		A1			A2			A3			A4		
		x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)	x (ft)	y (ft)	$\dot{h}$ (ft/s)
W1	Sample	4	4	4	8	9	9	9	9	9	5	5	5
	Mean	762.5	8.0	5.27	672.5	-2.22	8.42	885.5	-3.0	7.14	870	-8.0	5.66
	σ	217.5	8.37	2.62	327	12.02	6.02	402.8	22.14	4.15	664.8	25.88	4.04
W2 and W3	Sample	6	6	6	25	24	25	20	22	22	6	6	6
	Mean	1460	0	4.01	1533	-1.67	4.55	1190.5	-0.91	5.45	1430	5	5.22
	σ	505.8	0	1.19	678.6	15.79	1.95	523.9	25.24	3.07	525	10	2.31
W4 and W5	Sample	11	10	11	18	17	19	17	18	17	6	6	6
	Mean	939	4.0	4.49	1317	8.24	4.56	1476	-5.56	5.07	1200	-5	5.42
	σ	381.4	5.16	2.03	470	18.79	1.91	503.4	19.77	2.18	344.7	5.48	1.99
W6	Sample				6	7	7	6	6	6	3	3	3
	Mean				2153	4.29	6.89	2458	10.83	6.13	2017	0	9.27
	σ				988.1	34.57	3.95	506.4	28	4.65	1053.8	20	2.59
W7	Sample	1	1	1	10	11	11	5	5	5	1	1	1
	Mean	700	30	6.8	2271	0	5.44	2190	4	4.34	2200	-20	6.3
	σ	-	-	-	636	21.45	1.88	941	15.17	2.23	-	-	-
W8	Sample				5	5	5	3	3	3	2	2	2
	Mean				2080	8	4.0	2517	23.33	6.03	2250	0	5.3
	σ				760.3	8.37	1.79	632.9	32.14	4.61	170.3	0	4.24

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No.	Author	Title, etc
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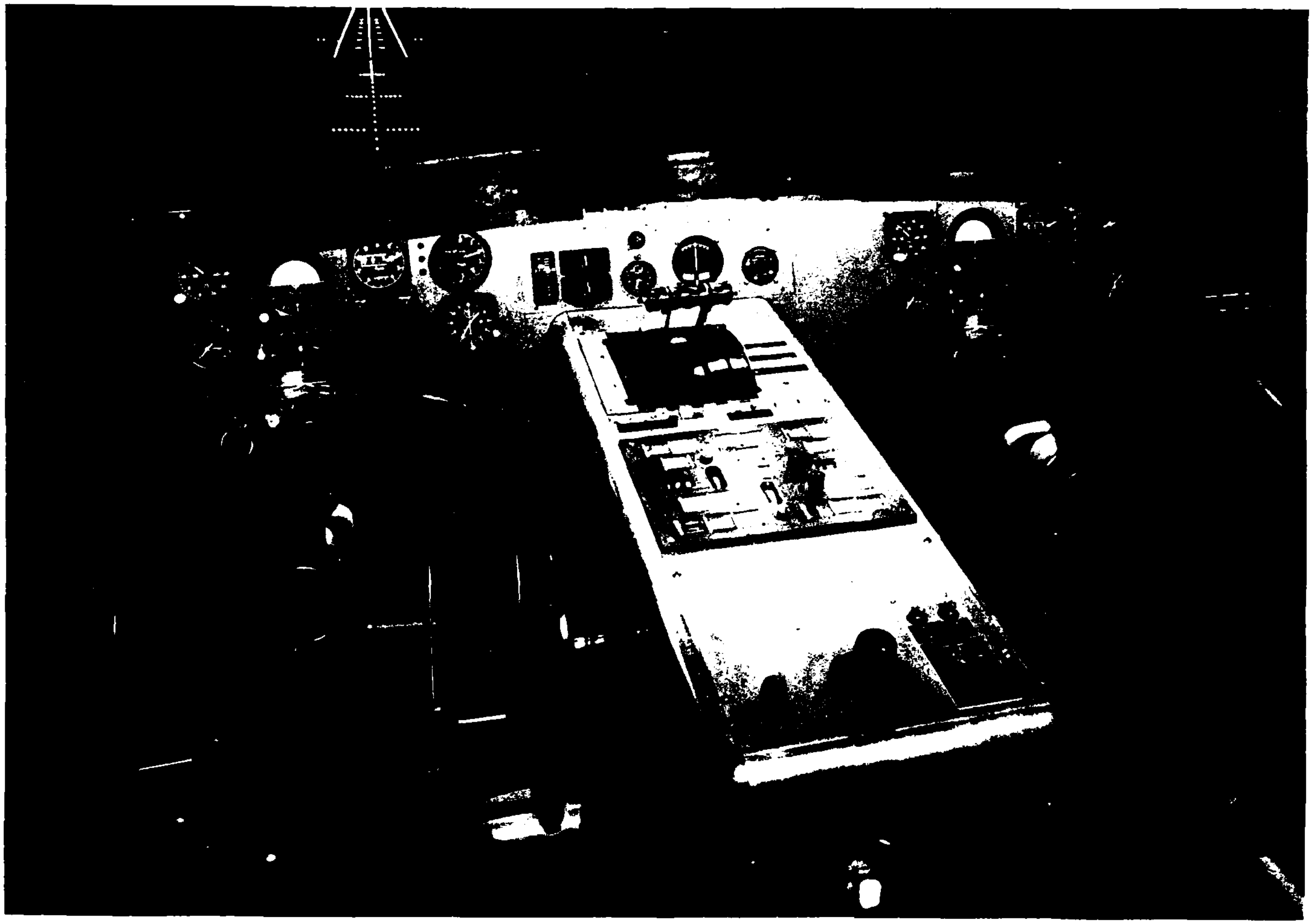


Fig 1 Cockpit layout

Fig 2

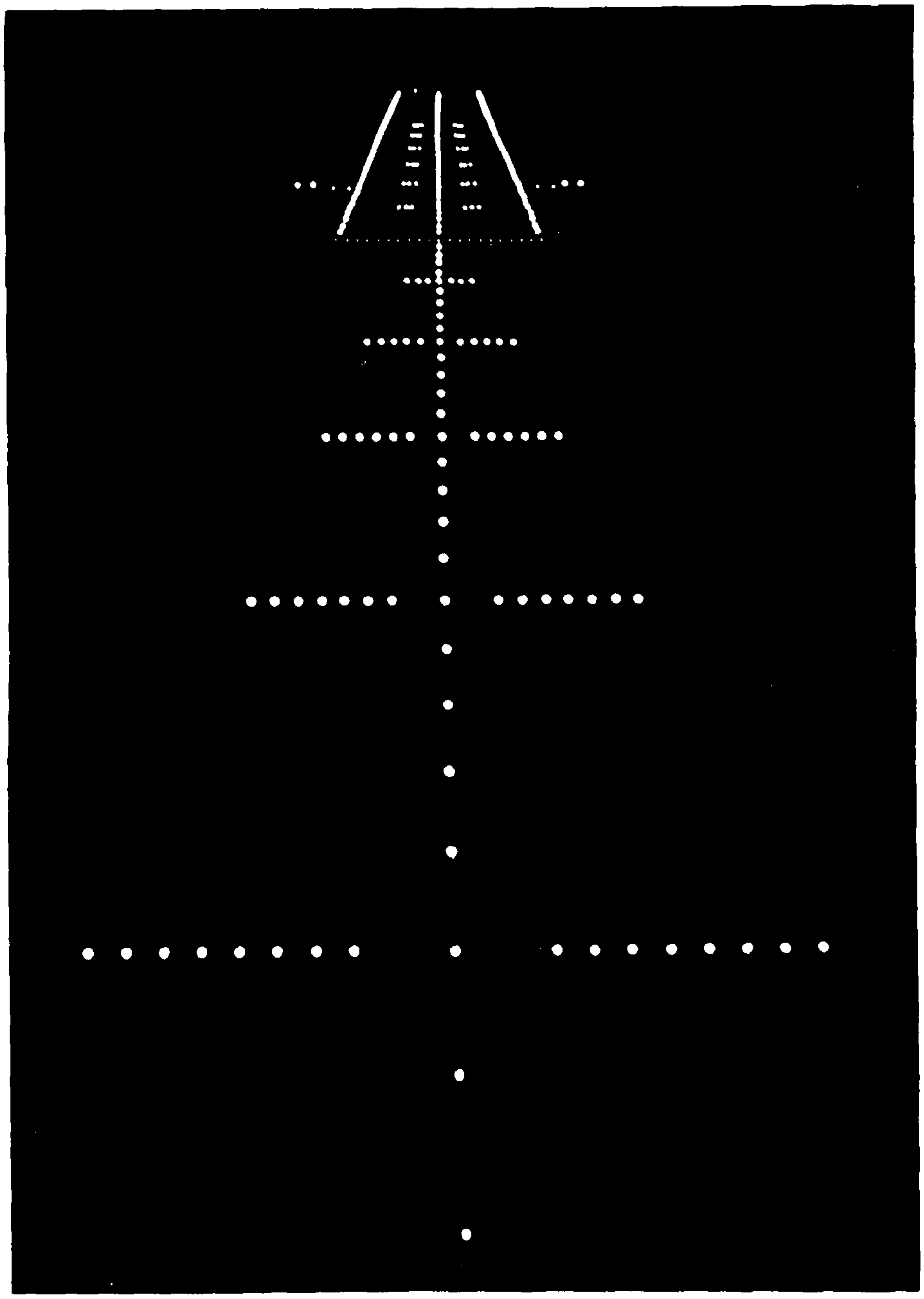


Fig 2 Lighting pattern (from a height of 215 ft; 4300 ft from glide-path origin)

TR 79126 C15784

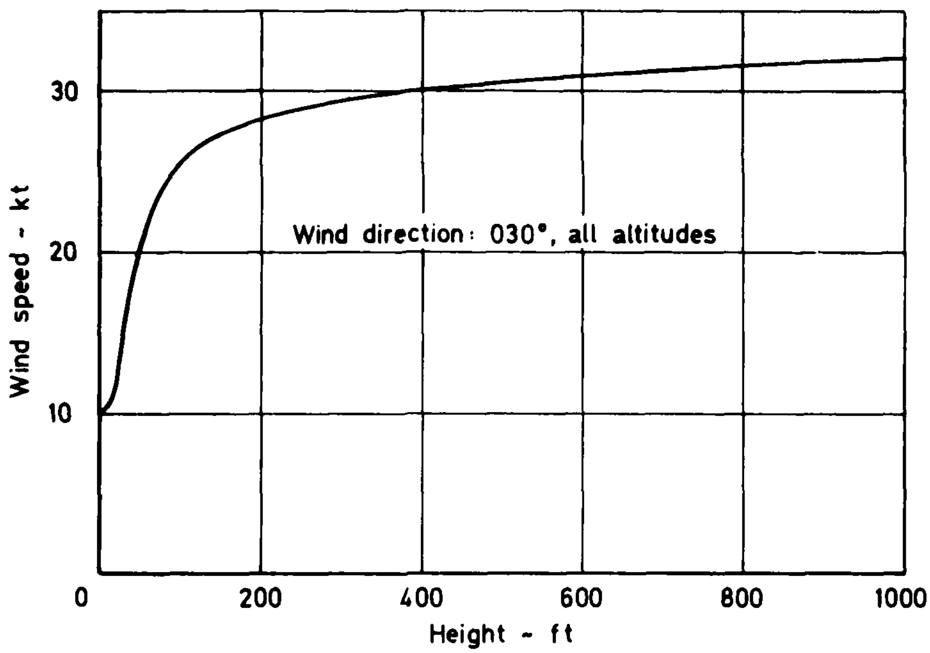


Fig 3 Unusual boundary layer (W1)

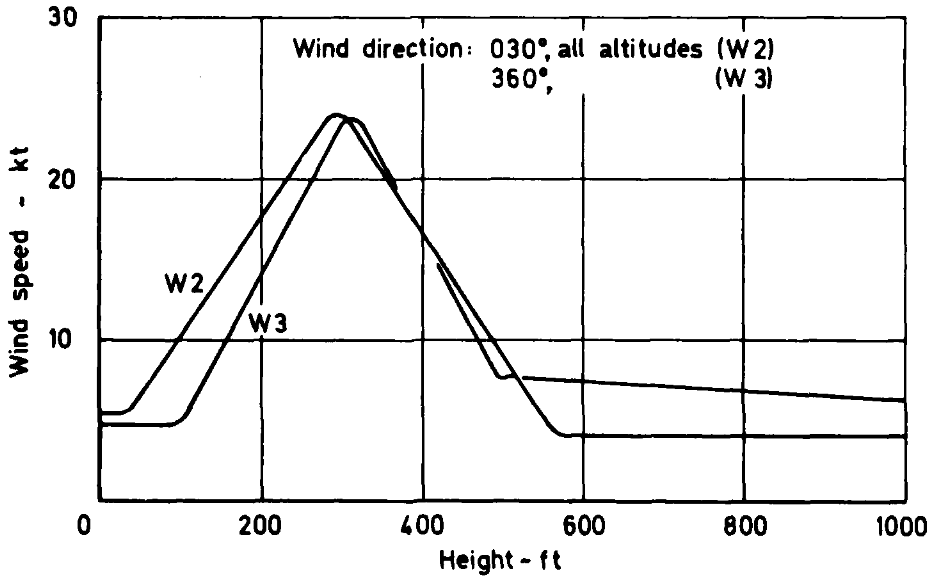


Fig 4 Low level-jet (W2, W3)

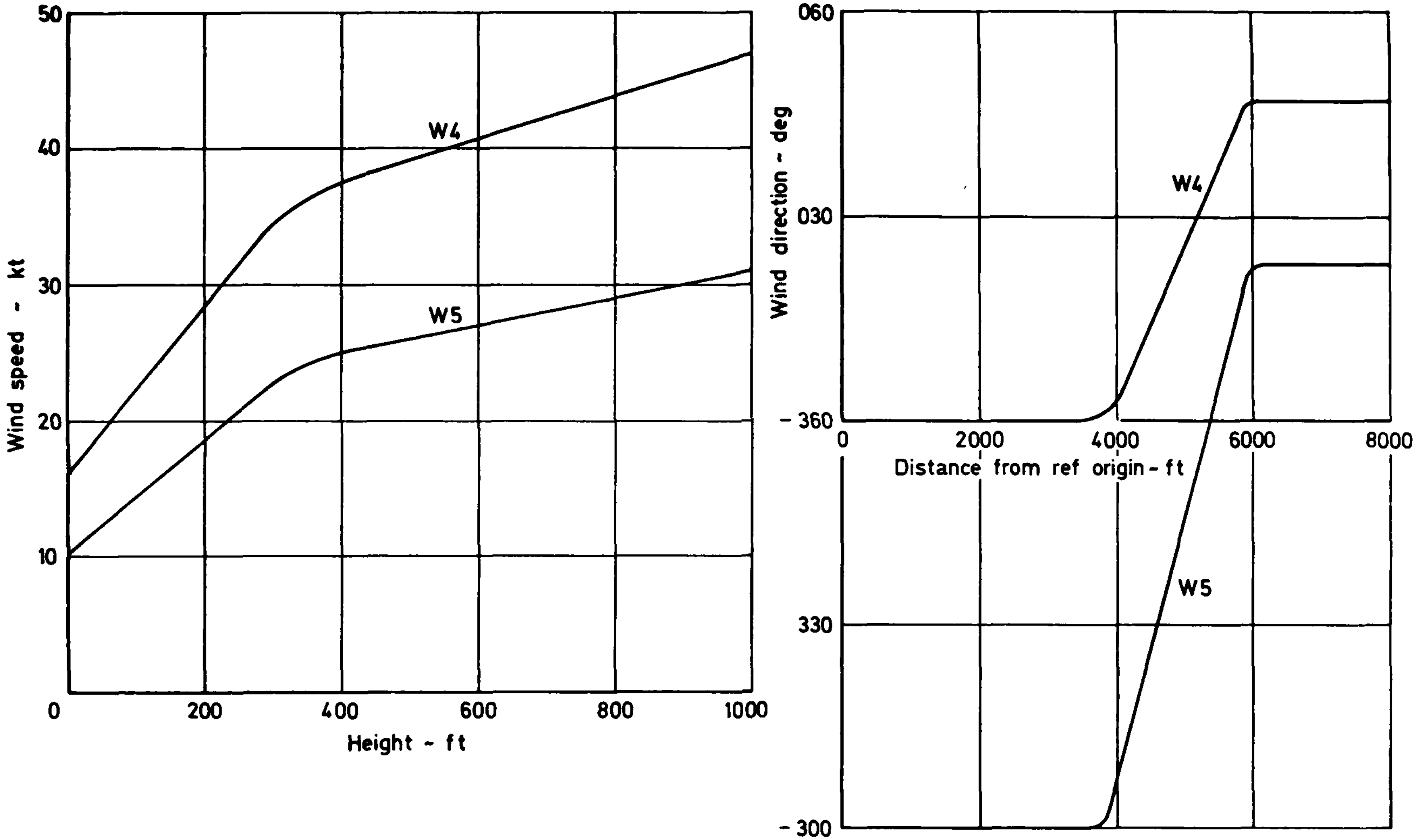


Fig 5 Variation of wind speed and direction through fronts (W4, W5)

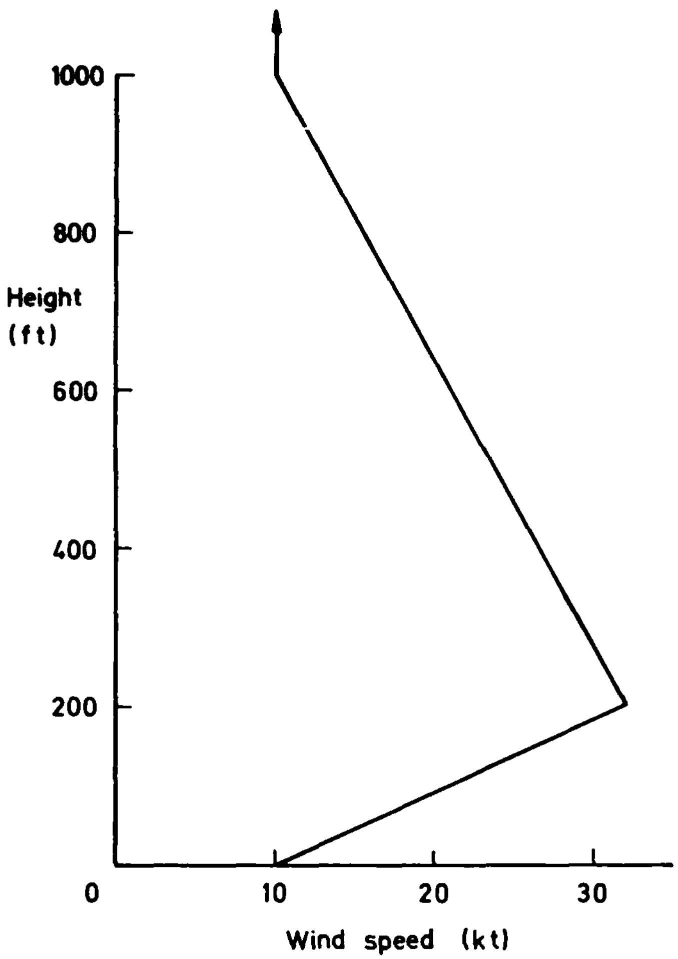


Fig 6 Basic profile for storm cells

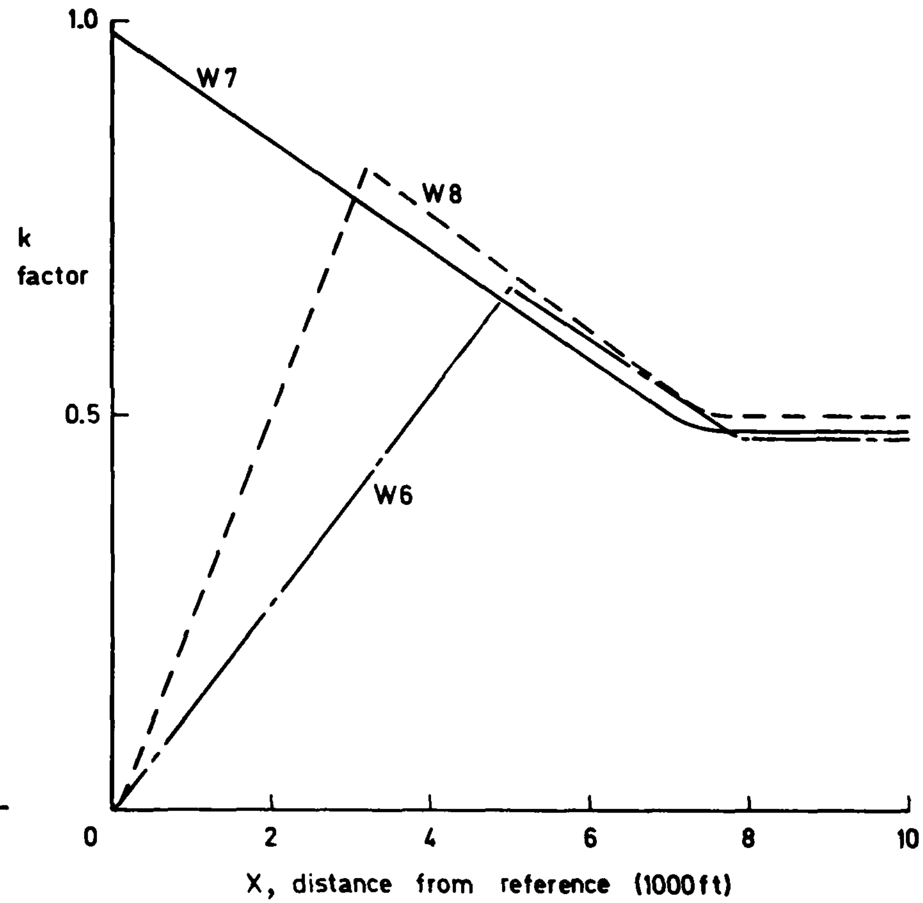


Fig 7 Multiplying factors on basic profile

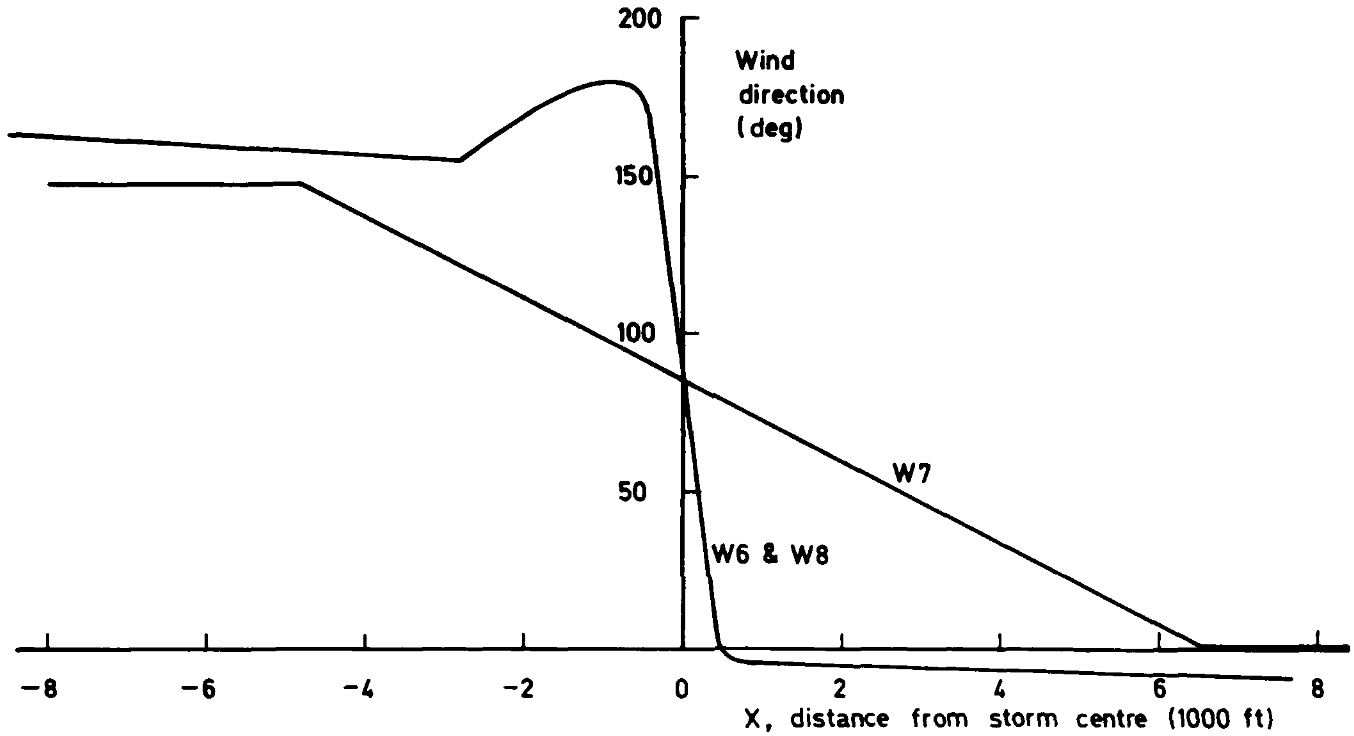


Fig 8 Variation of wind direction in storms

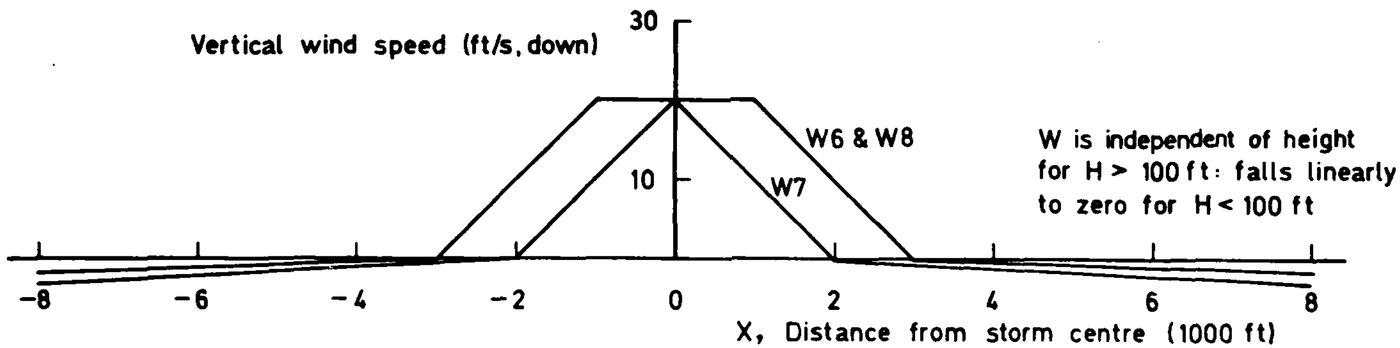


Fig 9 Vertical wind component, w, in storms

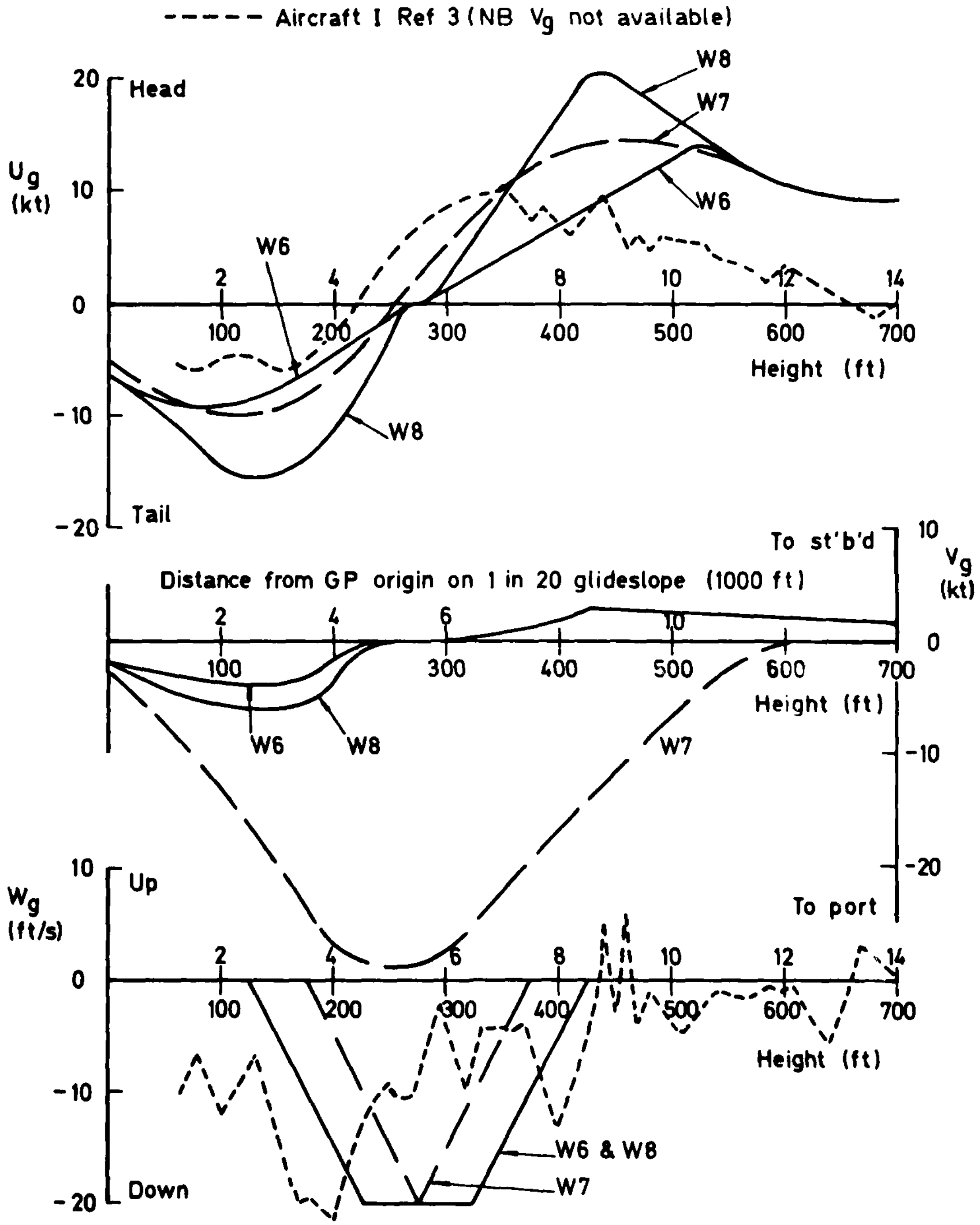


Fig 10 Velocity components encountered in storms on a 1 in 20 glide path

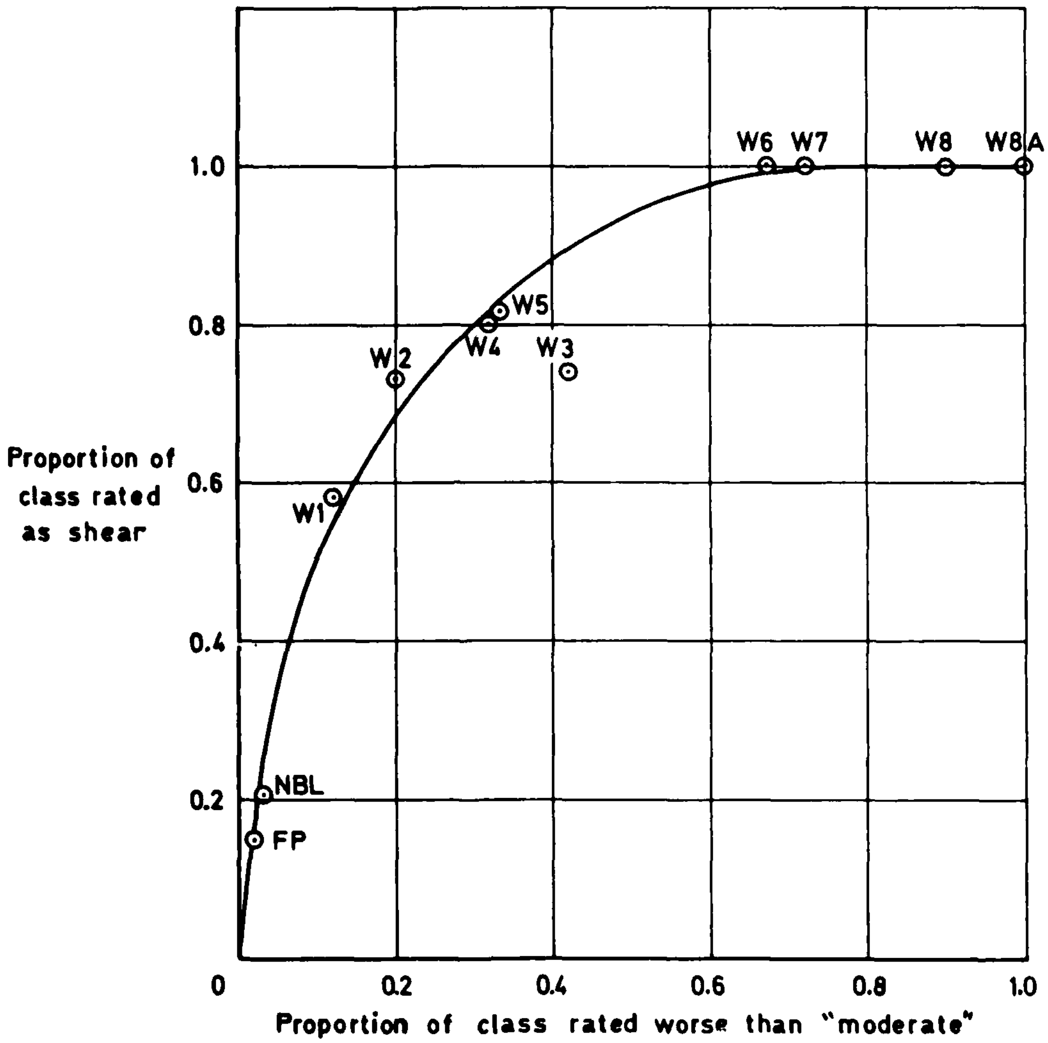


Fig 11 Success in shear recognition versus severity of shear

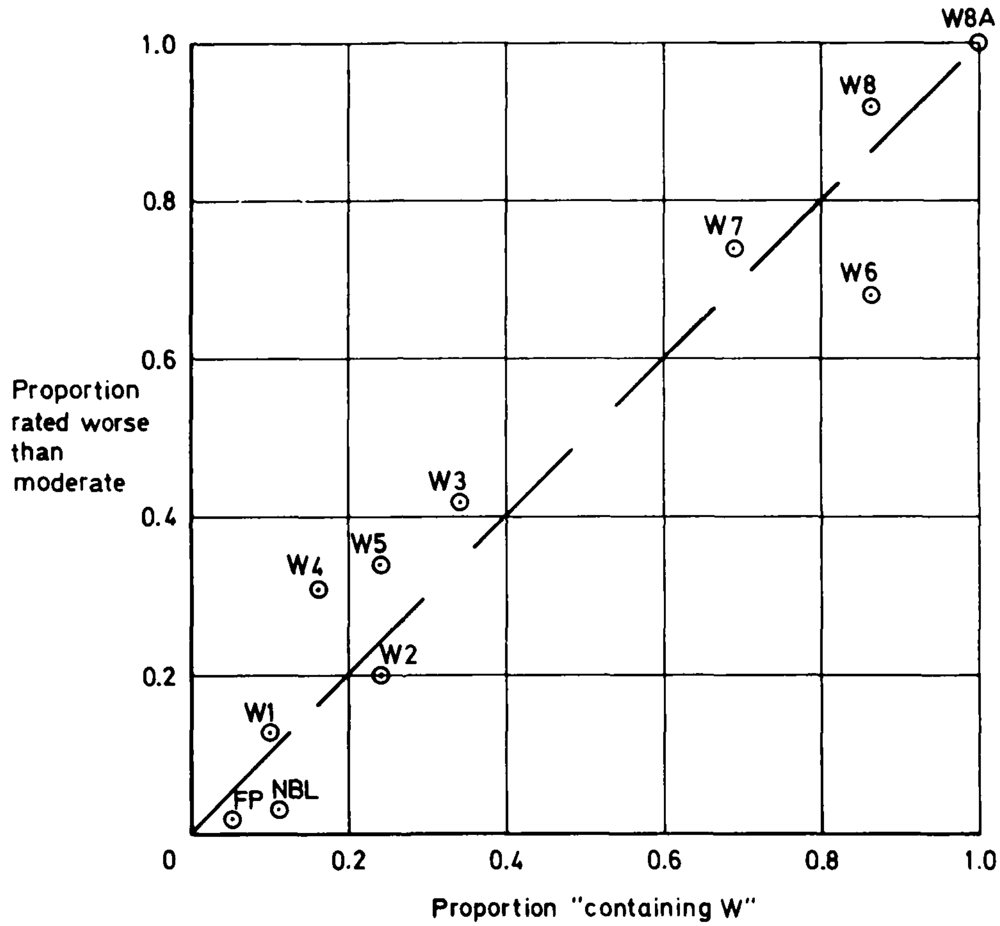
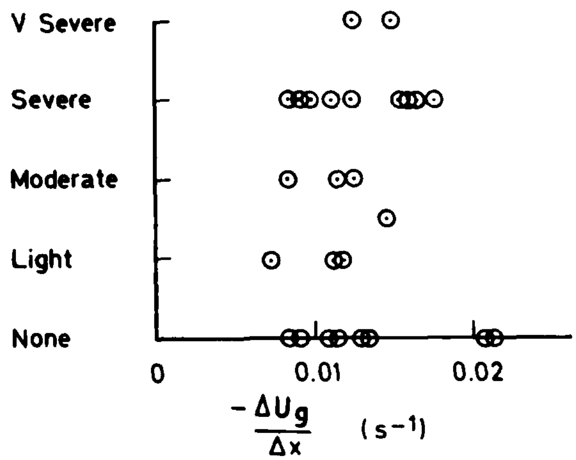
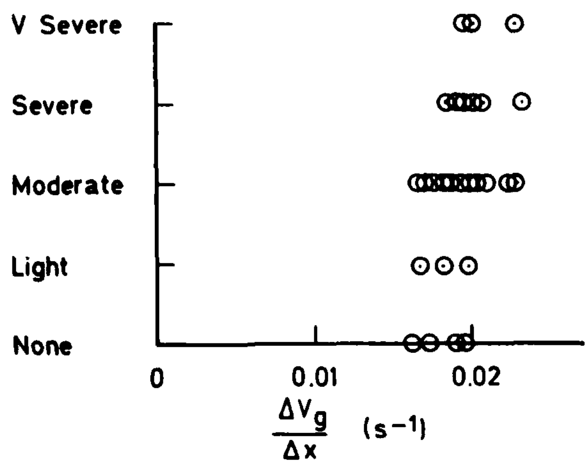


Fig 12 Correlation of severity of shear with perception of down draught



a Low-level jet (W3)



b Front (W4)

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Fig 13 Variation of rating with gradient for two types of shear

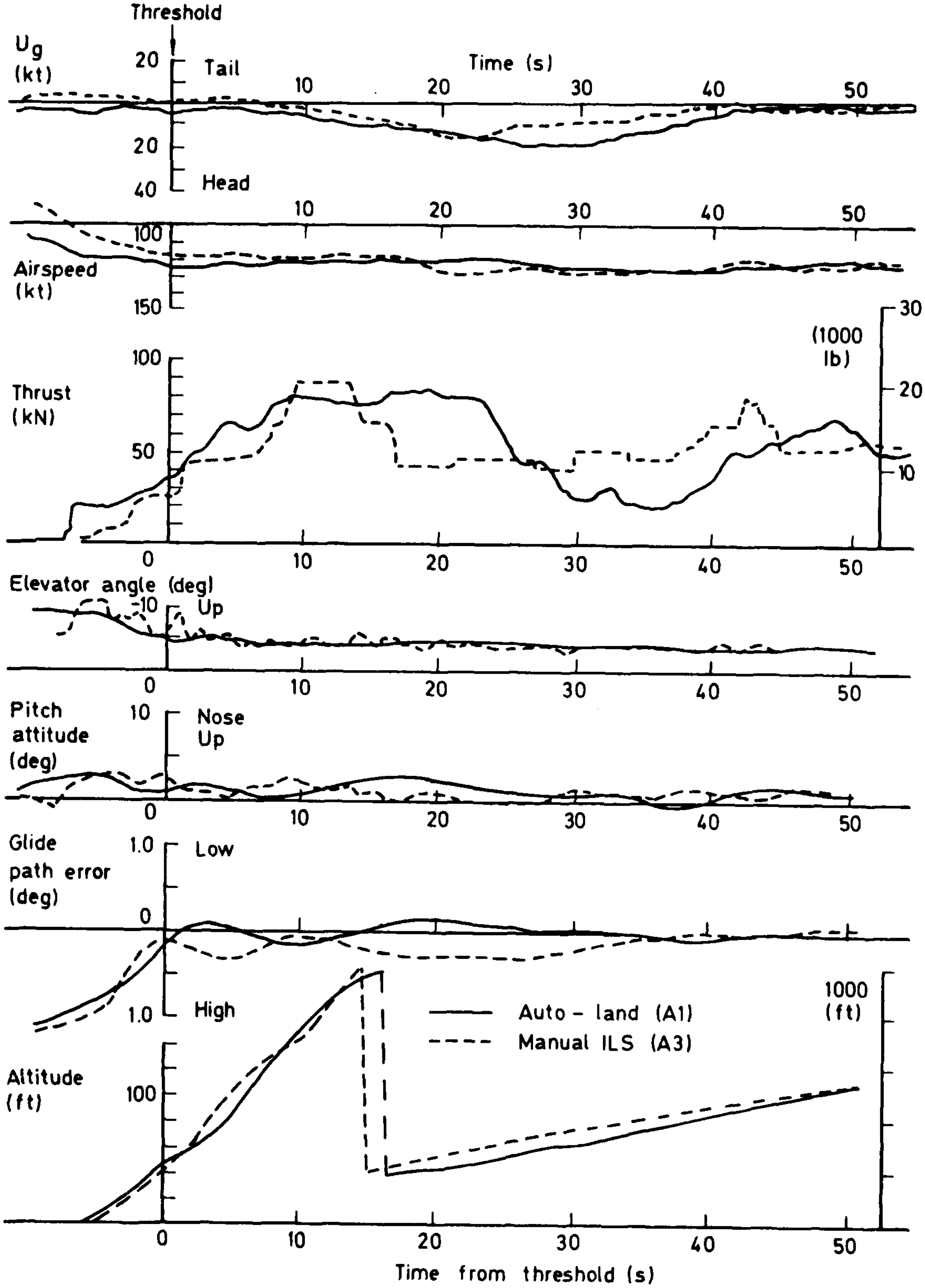

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Fig 14 Encounters with low-level jet (W3)

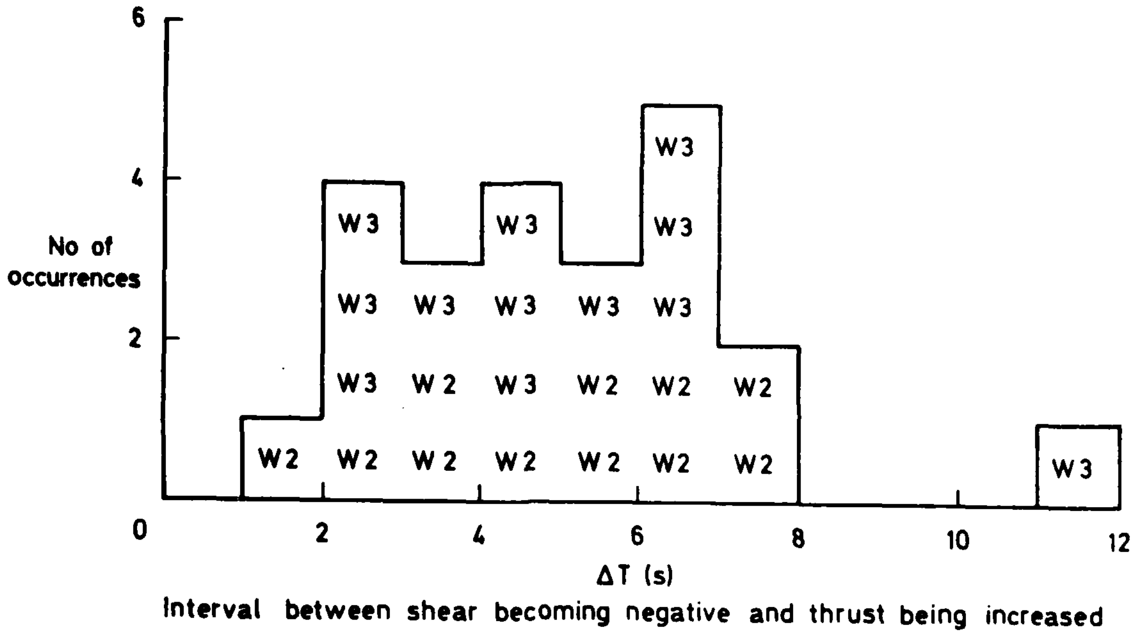

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Fig 15 Delay in response to low-level jets

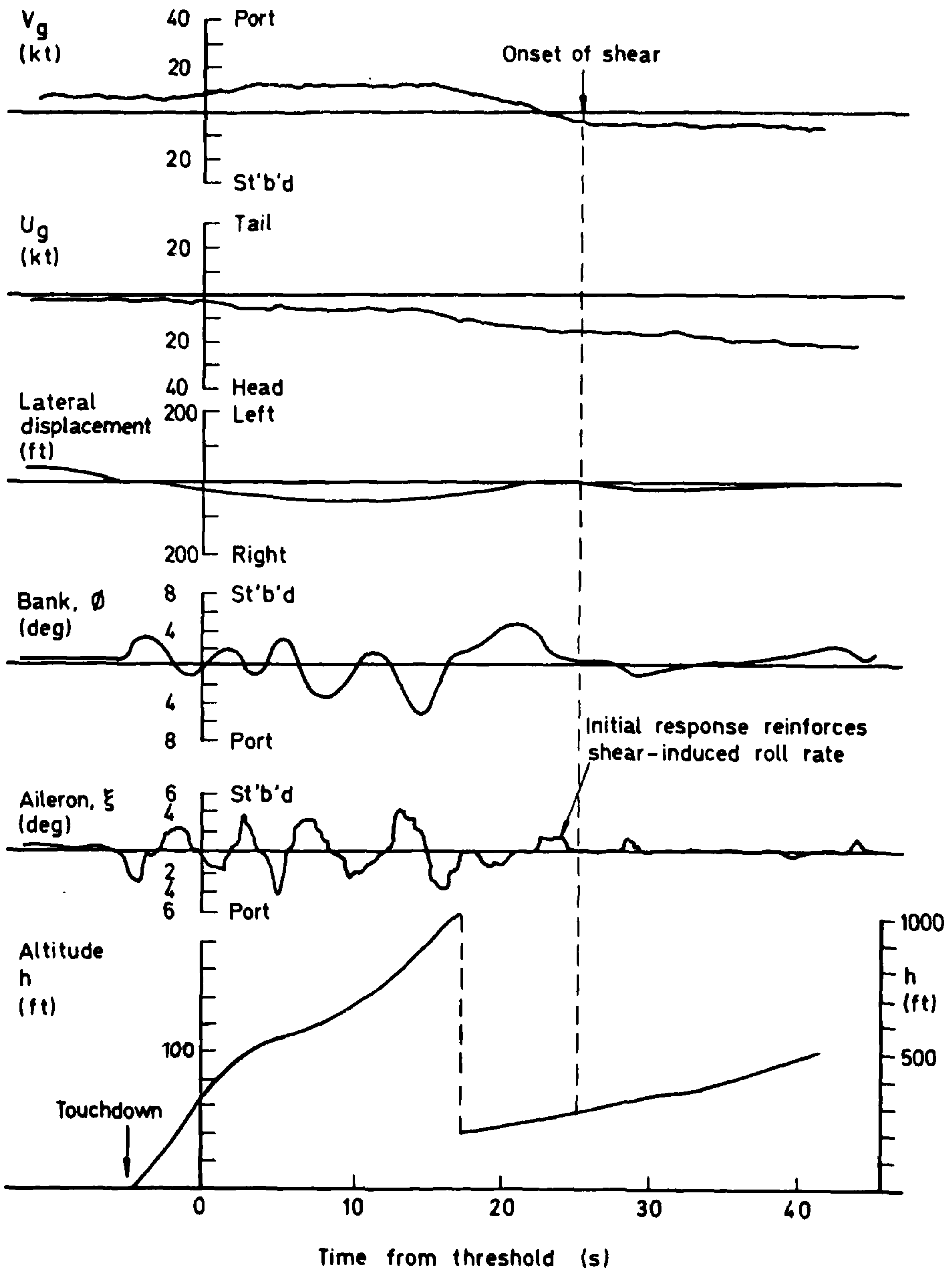

Fig 16 Encounter with front (W5) during manual ILS approach (rated moderate)

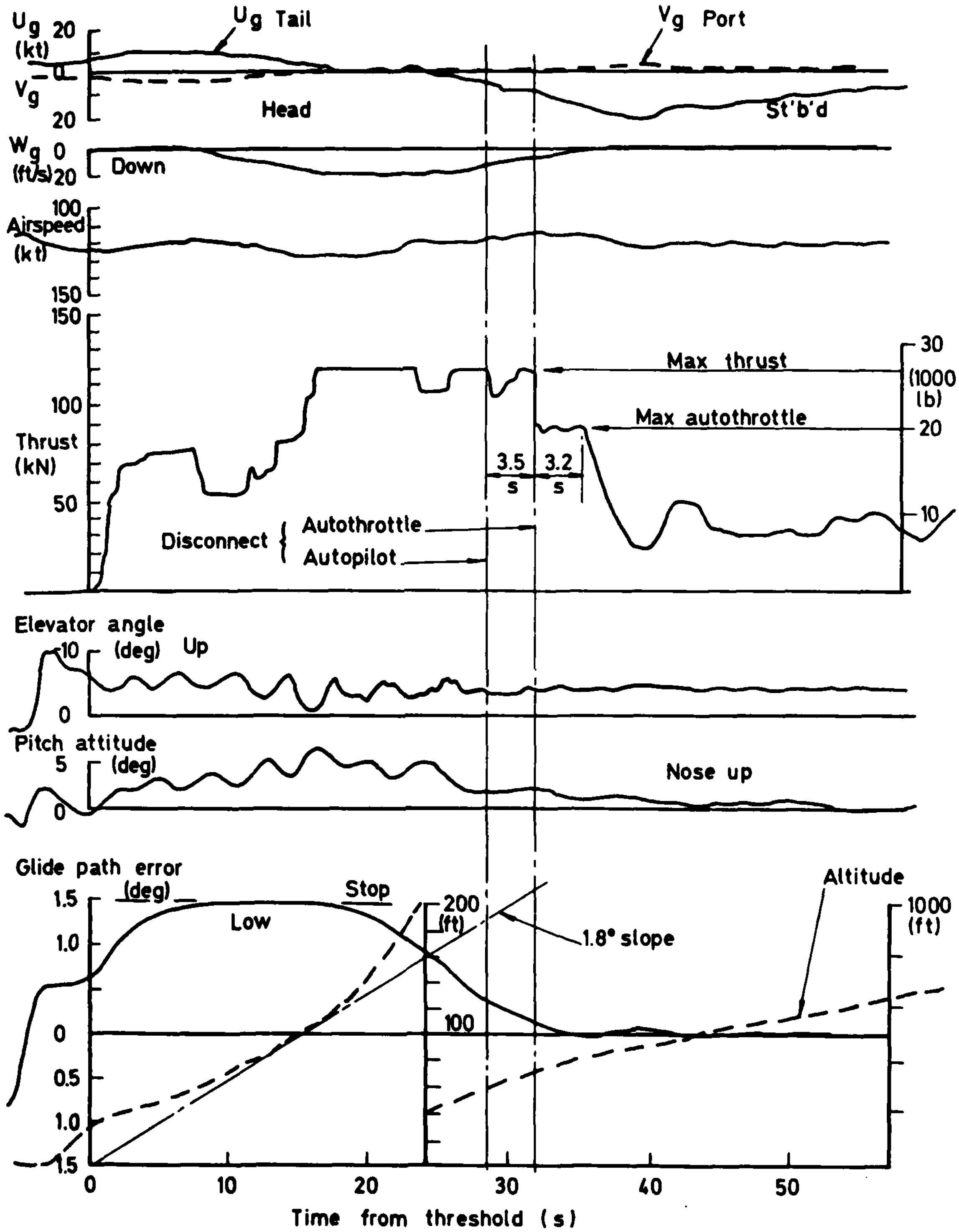

Fig 17 Encounter with storm cell (W8) during coupled approach (A2) (rated severe)

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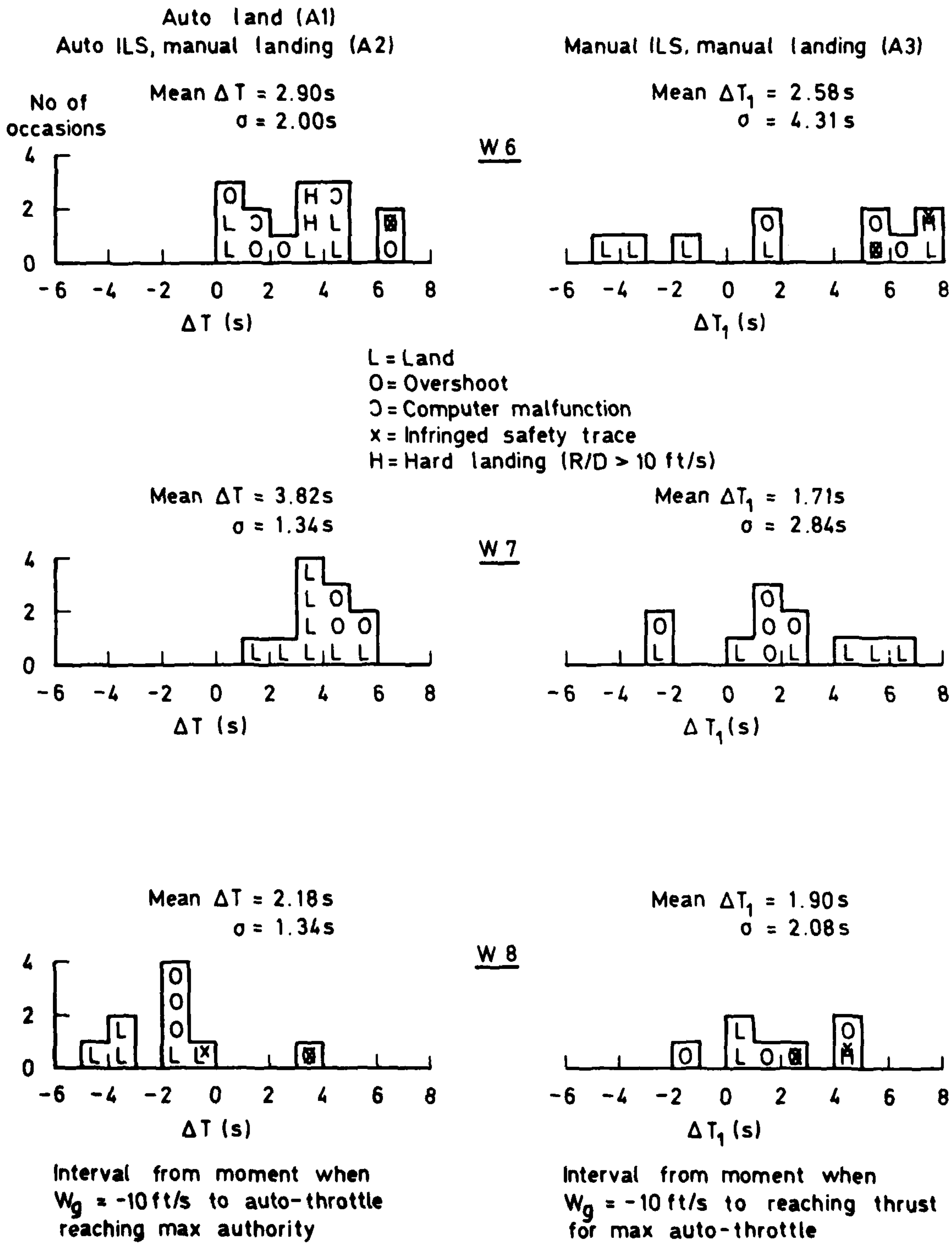

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Fig 18 Delay in response to storms

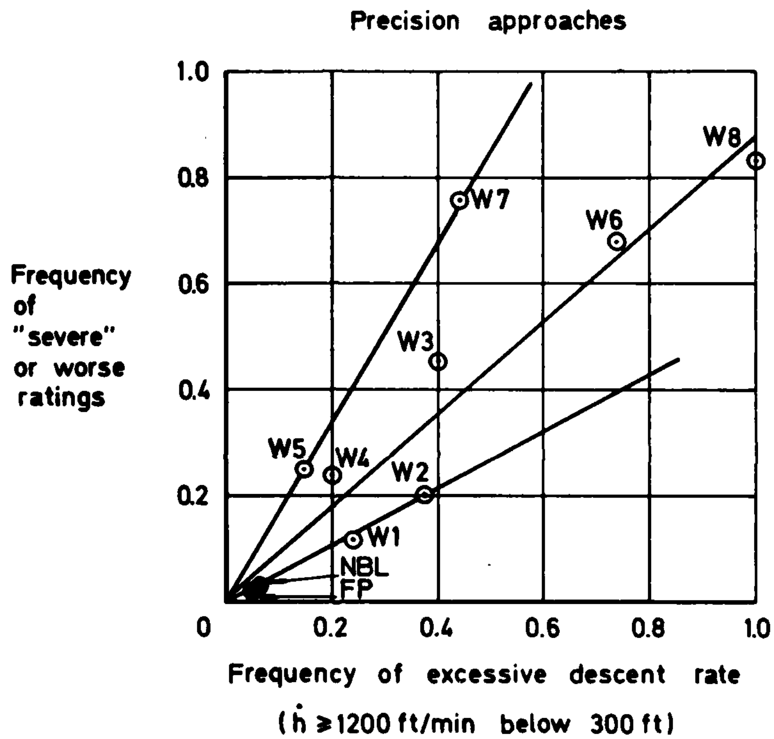

Fig 19 Severity of shear versus exceedances of approach descent rate

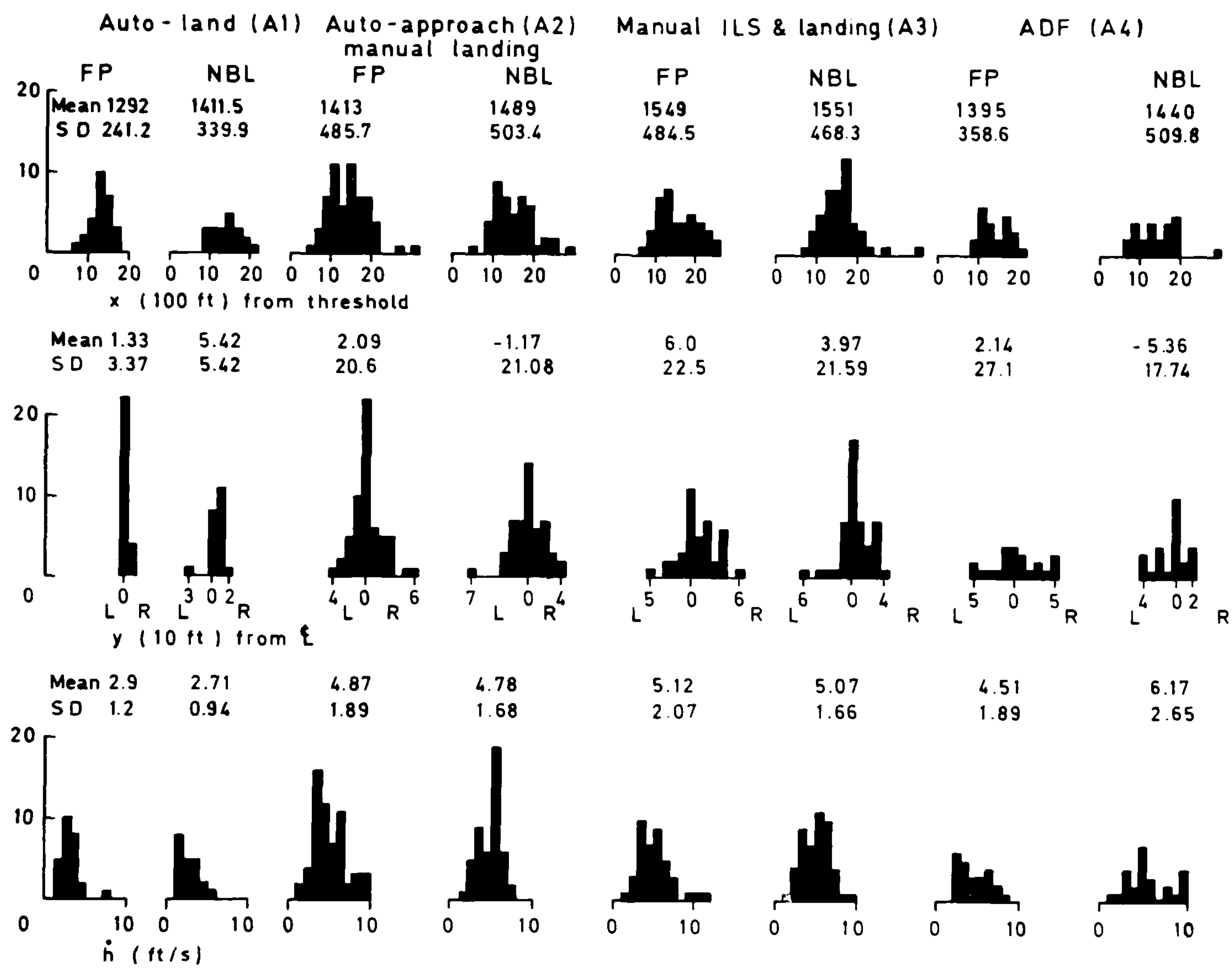

Fig 20 Touchdown performance (non-shears)

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED UNLIMITED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

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Wind-shear.

17. Abstract

A study has been made in a fixed-base simulator of encounters with a variety of idealised wind-shears under conditions simulating a two-pilot approach, partly on instruments and partly visual, made at night.

Twenty-five pilots, airline and Service, participated completing a total of 62 sorties, each of ten approaches. There were four shear encounters per sortie. The data comprised time-histories of each approach together with the pilots' responses to a detailed questionnaire and their spontaneous observations.

Pilots were successful in recognising the absence of shear or the presence of severe shear. They were less successful in recognising shears of moderate intensity or in identifying the velocity components. They were prone to discern vertical draughts where none existed and may have been induced to do so by the compelling visual indications of vertical departure from the glide-path given by the Precision Approach Path Indicator (PAPI).

To cope effectively with the shears, pilot action had to be both prompt and appropriate and it was clear that pilots were quick to seek clues that might offer 'early warning' of impending shear. Many pilots commented on the value of participating in this study and it seems likely that the inclusion of shear encounters during routine simulator training may prove beneficial.

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